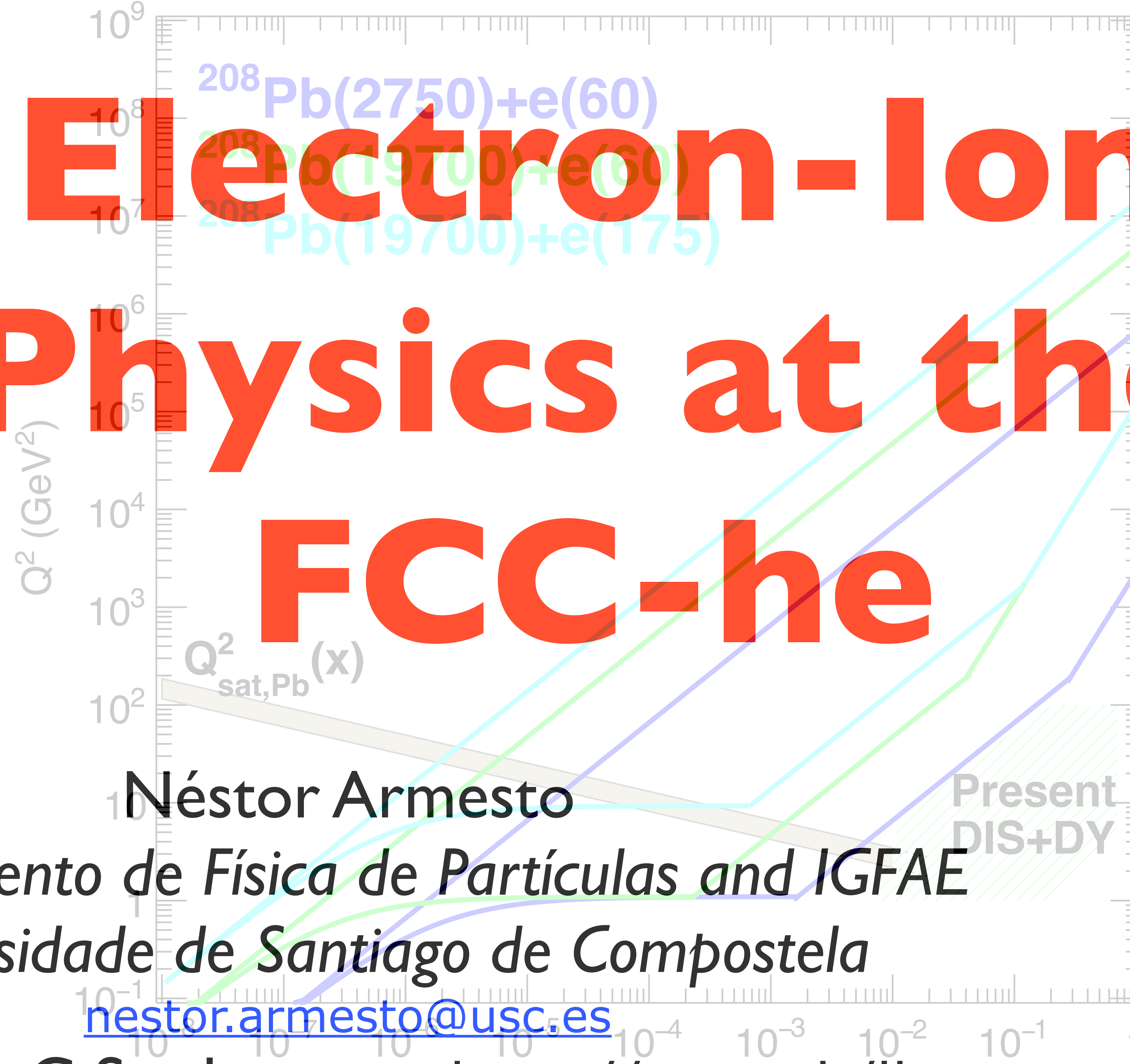
FCC Week 2016
Rome, April 12th 2016

Electron-Ion Physics at the FCC-he



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for the LHeC Study group, http://cern.ch/lhec

Contents:

1. Introduction.

2. Kinematics and luminosity.

3. Physics opportunities:
   - ➜ Nuclear parton densities nPDFs.
   - ➜ Diffraction.
   - ➜ QCD radiation and hadronisation in the nuclear medium.

4. Summary.

FCC-he case for eA is a kinematic extension of that at the LHeC.

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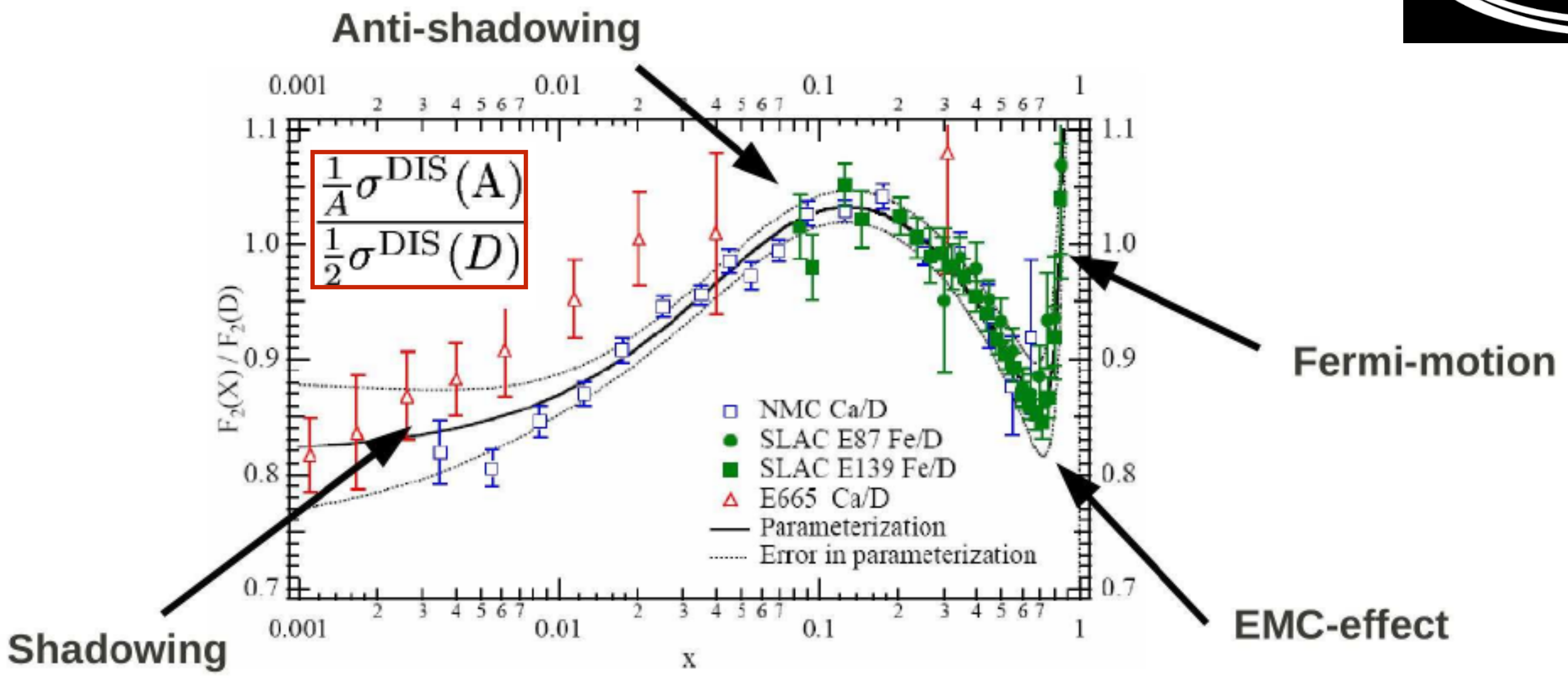
Motivation: nPDFs



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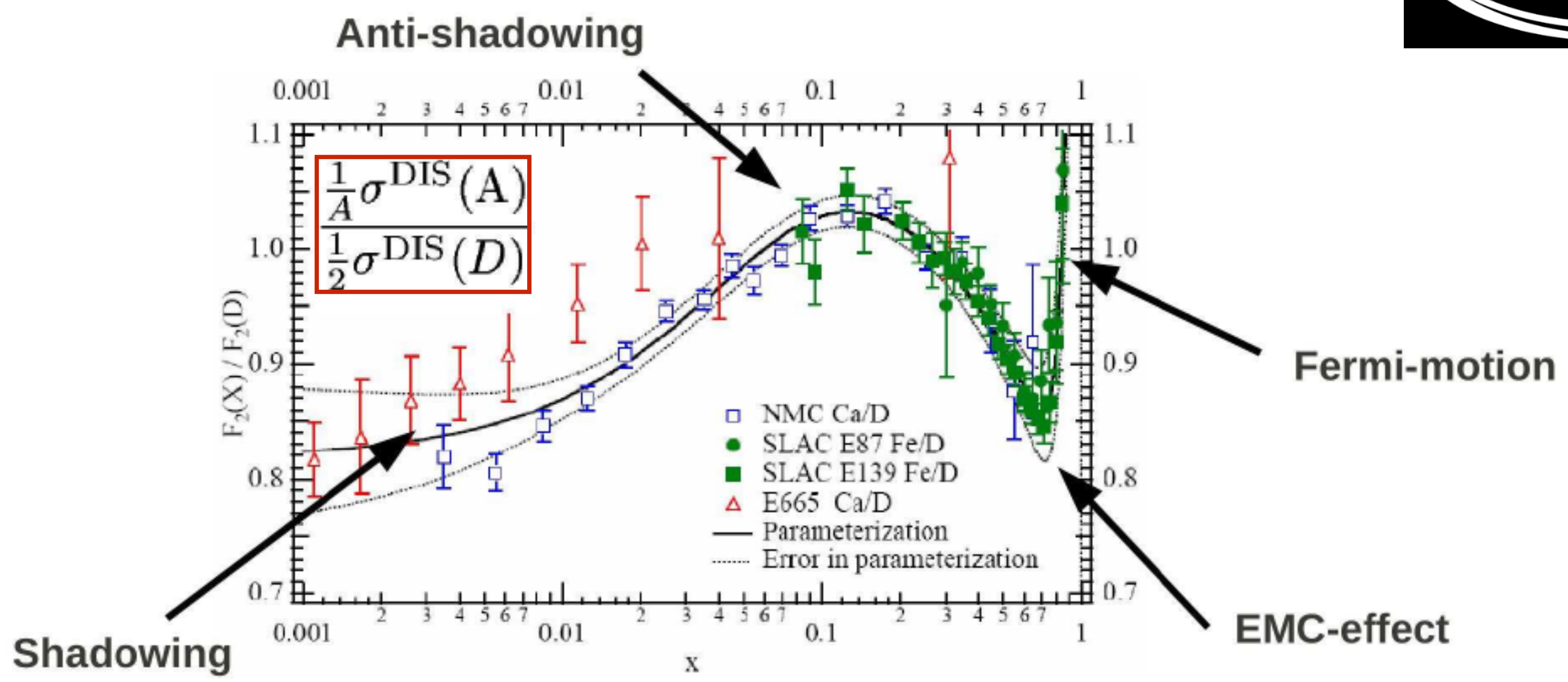

- Bound nucleon≠free nucleon: search for process independent nPDFs that realise this condition, assuming collinear factorisation.

$$\sigma_{\rm DIS}^{\ell+A\to\ell+X} = \sum_{i=q,\overline{q},g} f_i^A(\mu^2) \otimes \hat{\sigma}_{\rm DIS}^{\ell+i\to\ell+X}(\mu^2)$$

Nuclear PDFs, obeying the standard DGLAP

Usual perturbative coefficient functions

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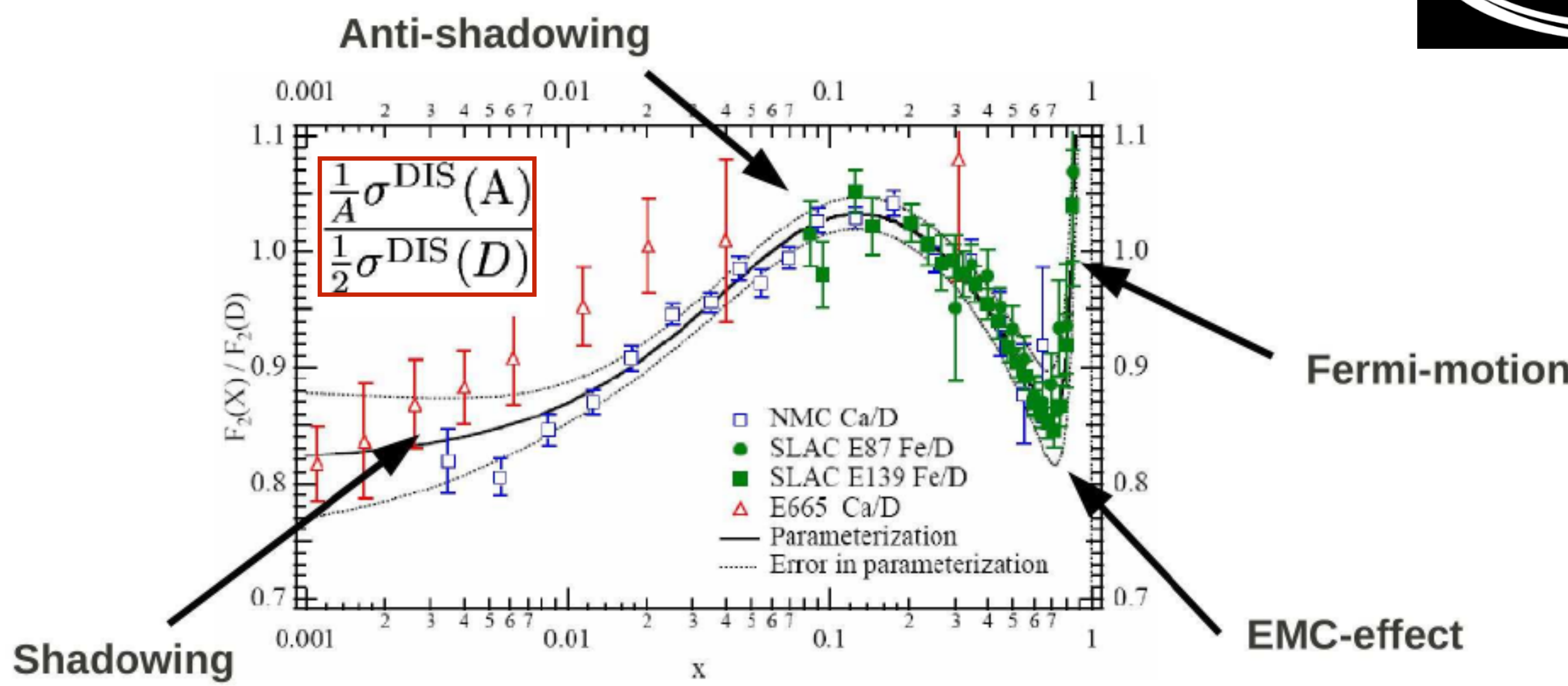

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Nuclear PDFs, obeying the standard DGLAP — **Usual perturbative coefficient functions**

$$f_i^{p,A}(x,Q^2) = R_i^A(x,Q^2) f_i^p(x,Q^2)$$

$$R = \frac{f_{i/A}}{A f_{i/p}} \approx \frac{\text{measured}}{\text{expected if no nuclear effects}}$$

Contemporary nPDF sets:

- Most commonly used sets:

item	HKN07	EPS09	DSSZ	nCTEQ	LHeC
Reference	Phys. Rev. C76 (2007) 065207	JHEP 0904 (2009) 065	Phys.Rev. D85 (2012) 074028	arXiv: 1509.00792	Workshops + this talk PRD(2030+)
Order pQCD	LO & NLO	LO & NLO	NLO	NLO	NNLO
NC e+A / e+d DIS	√	√	√	√	NC
Drell-Yan ll in p+A / p+d	√	√	√	√	--
RHIC pions in d+Au / p+p		√	√	√	--
Neutrino-nucleus DIS			√		CC
$\sqrt{Q^2}$ cut in DIS	1 GeV	1.3 GeV	1 GeV	2 GeV	free
# of data points	1241	929	1579	740	many
Free parameters	12	15	25	17	O(20)
Error sets available		√	√	√	(y)
Error tolerance $\Delta\chi^2$	13.7	50	30	35	1
Baseline	MRST98	CTEQ6.1	MSTW08	CTEQ6M?	None – or ep+eD+eA
Heavy quark treatment	ZM_VFNS	ZM_VFNS	GM_VFNS	GM_VFNS	s,c,b data

M. Klein at POETIC6

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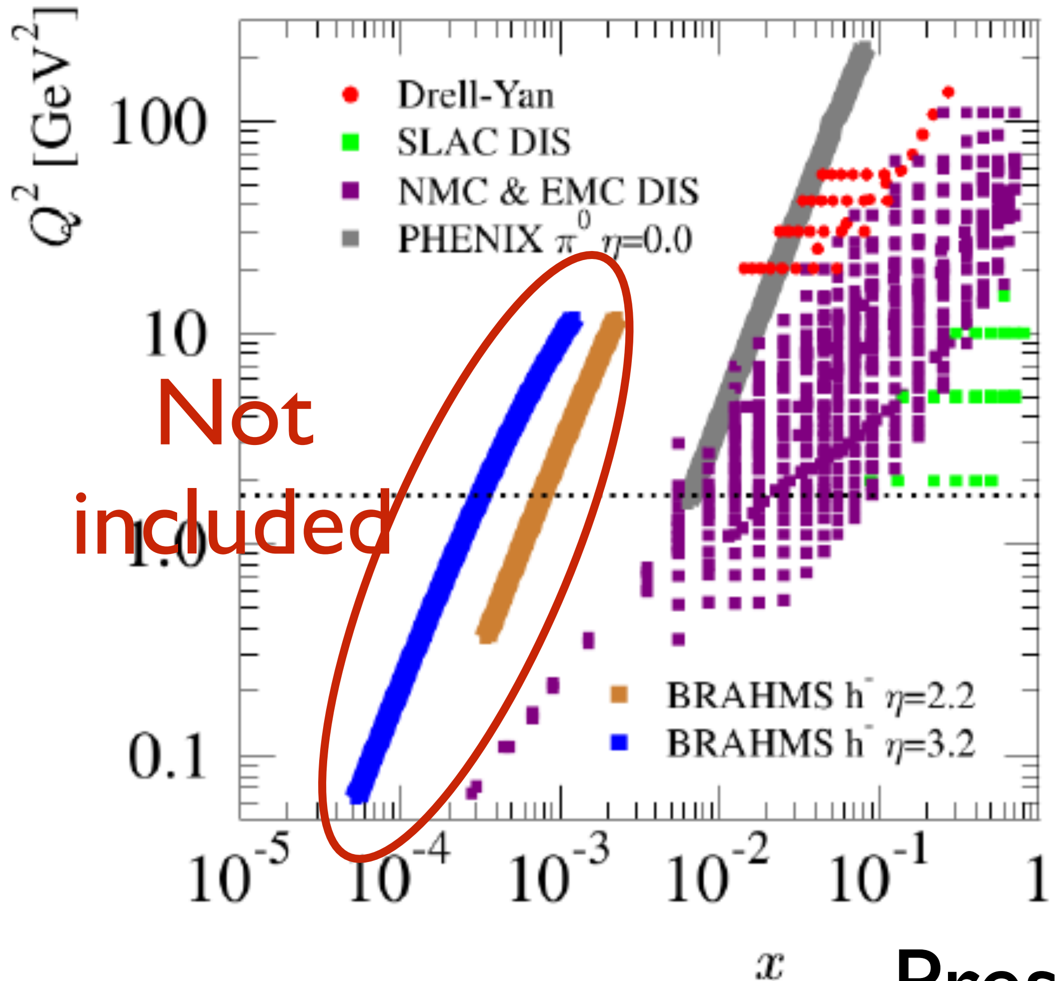
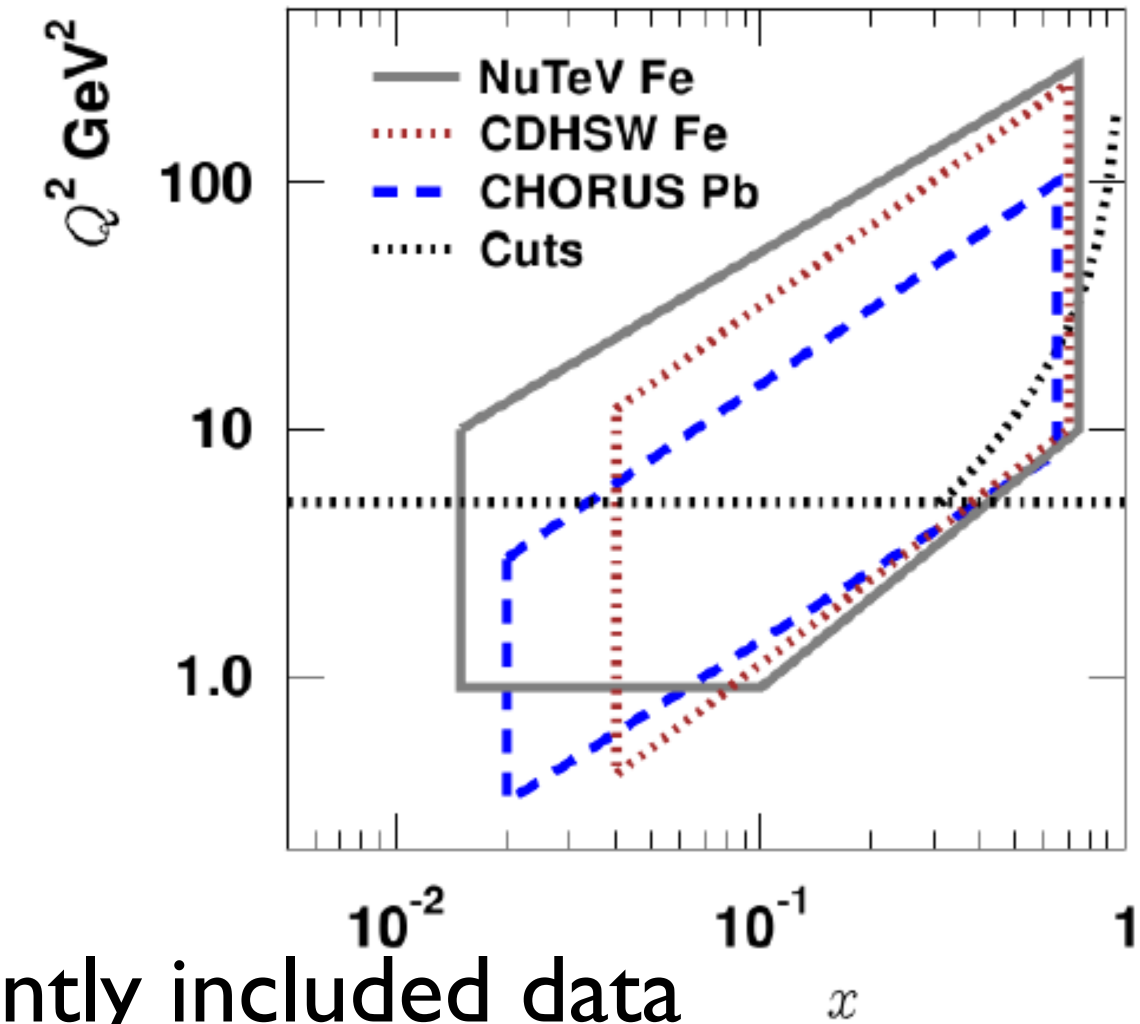
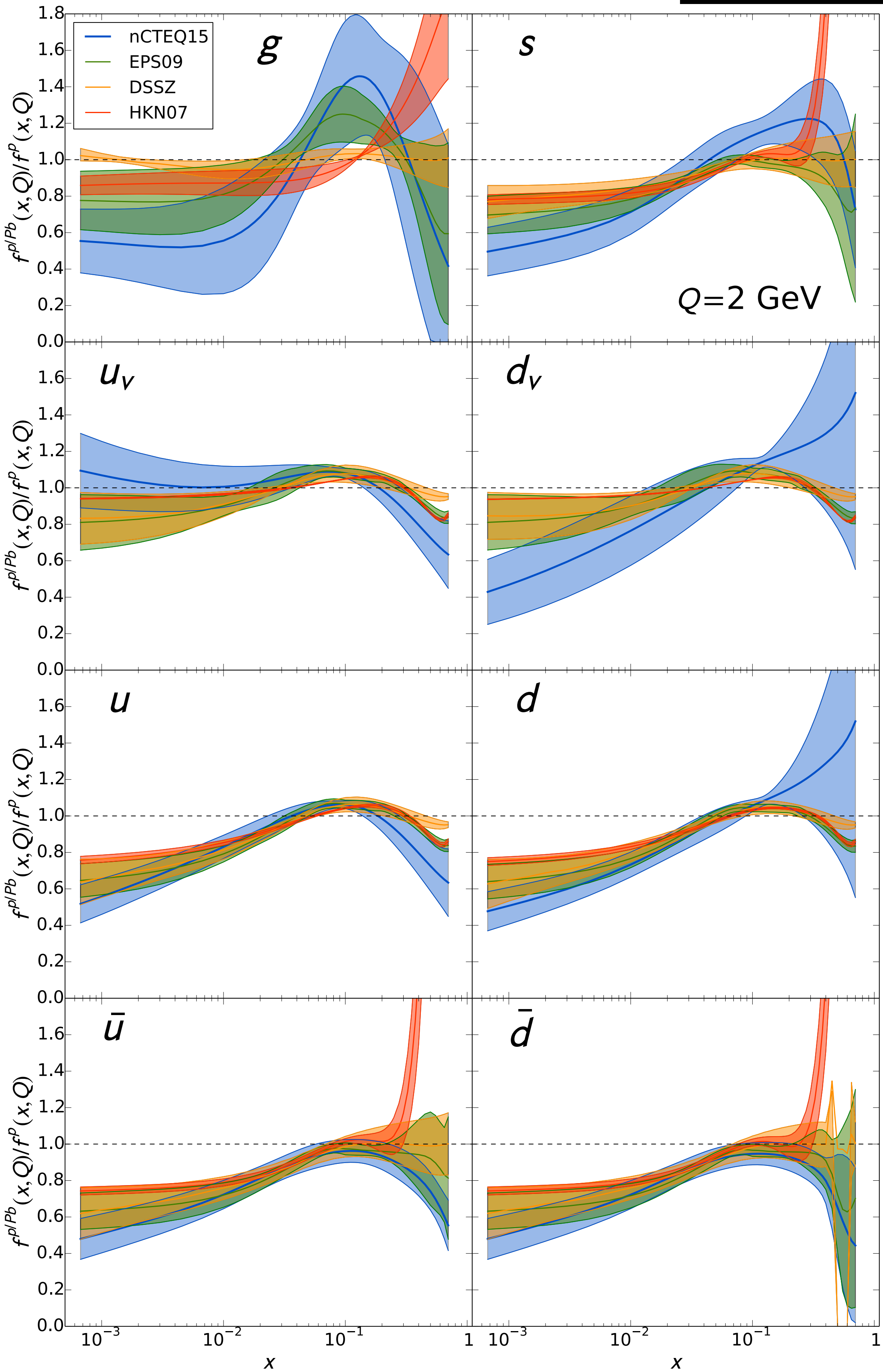




Presently included data

Contemporary nPDF sets:

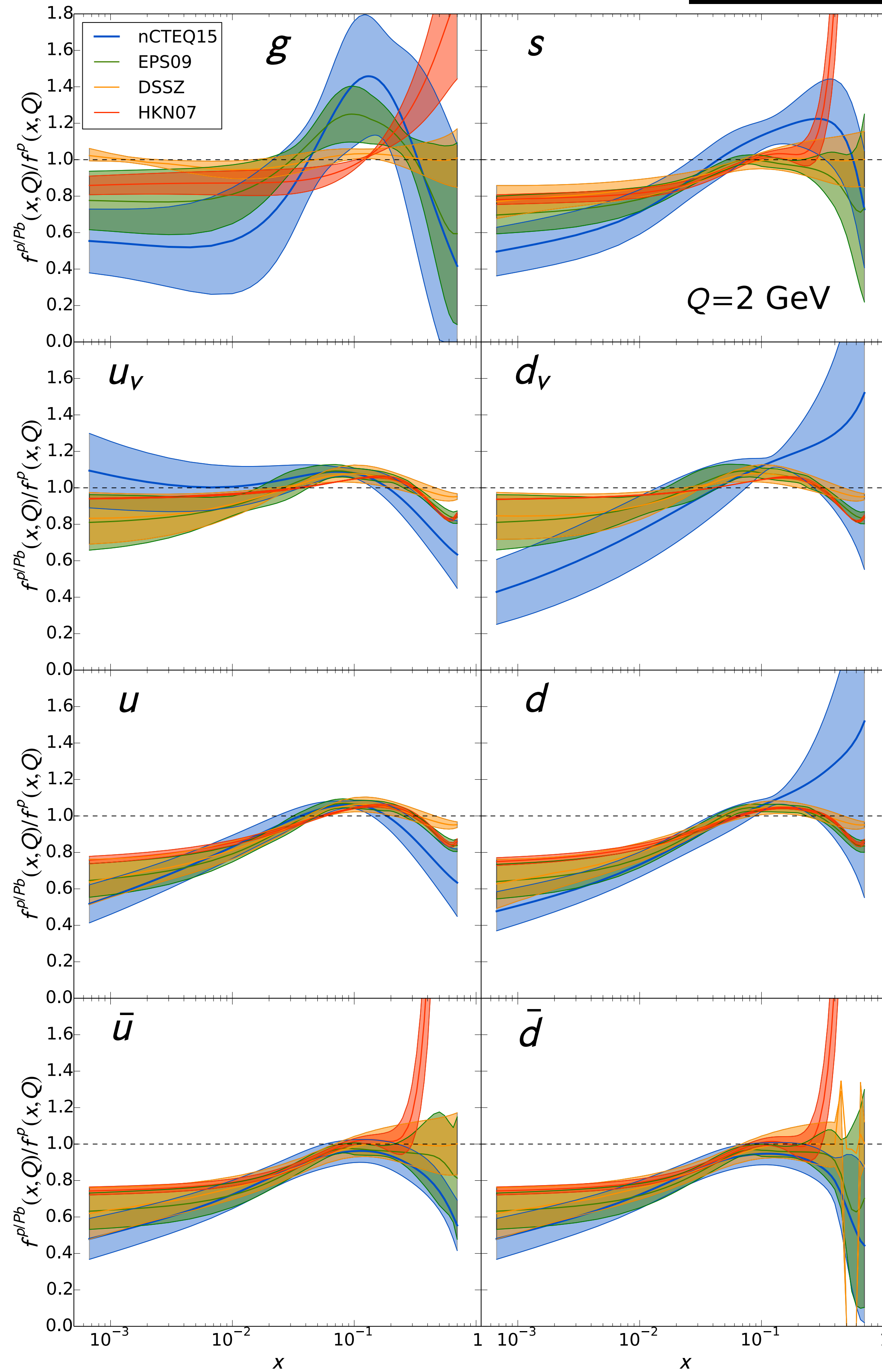
- Most commonly used sets:



Contemporary nPDF sets:

- Most commonly used sets:

- Uncertainties where there are no data.
- Glue presently unconstrained below $x=10^{-2}$.
- Differences (valence with nCTEQ: $R_d \neq R_u$) due to assumptions in initial conditions and data included.
- Problems for benchmarking in heavy-ion collisions: pPb@LHC.



High-energy QCD:

- Different alternatives (evolutions, factorisations) to describe small-x data from ep to AA collisions:
  - ➜ pQCD: DGLAP evolution (fixed order perturbation theory); resummation schemes: BFKL, CCFM, ABF, CCSS; non-linear dynamics (CGC).
  - ➜ Non-perturbative approaches: Regge theory, holographic models,…

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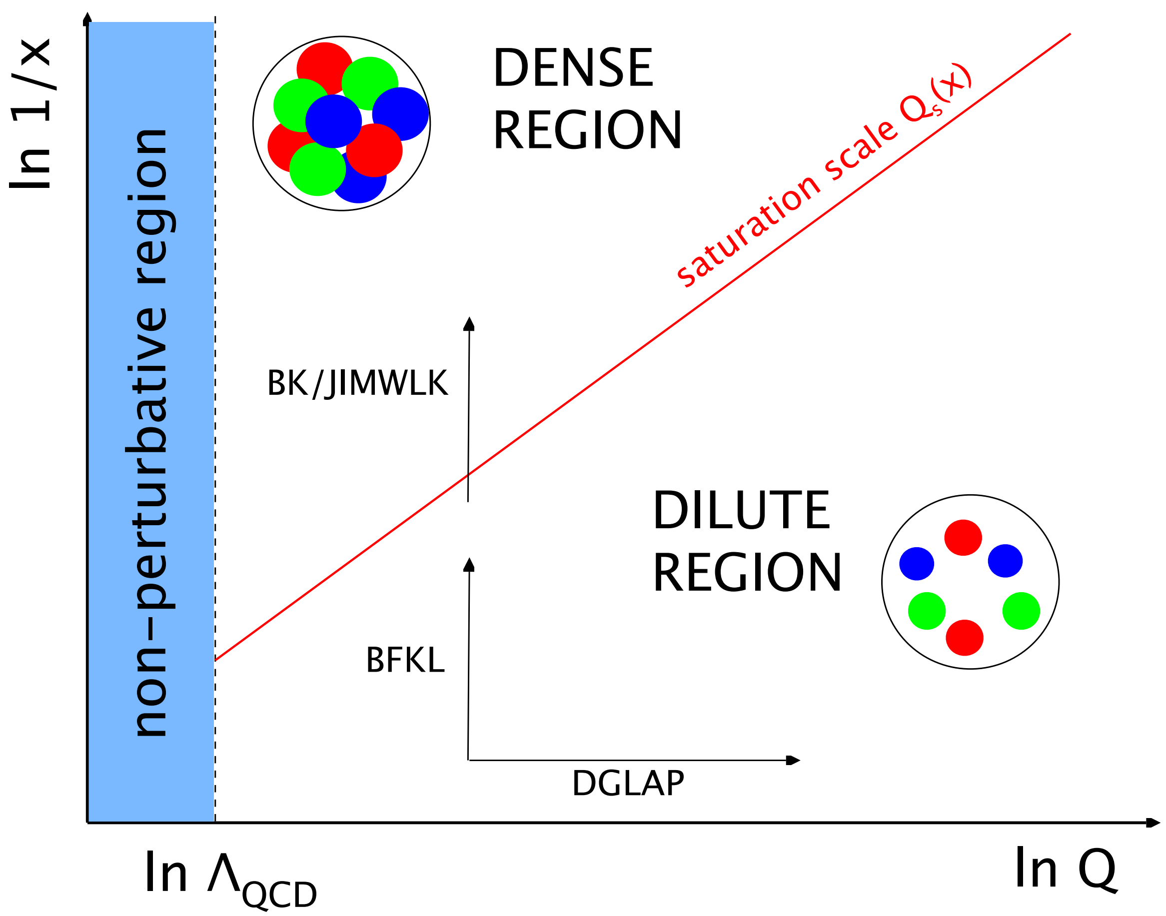
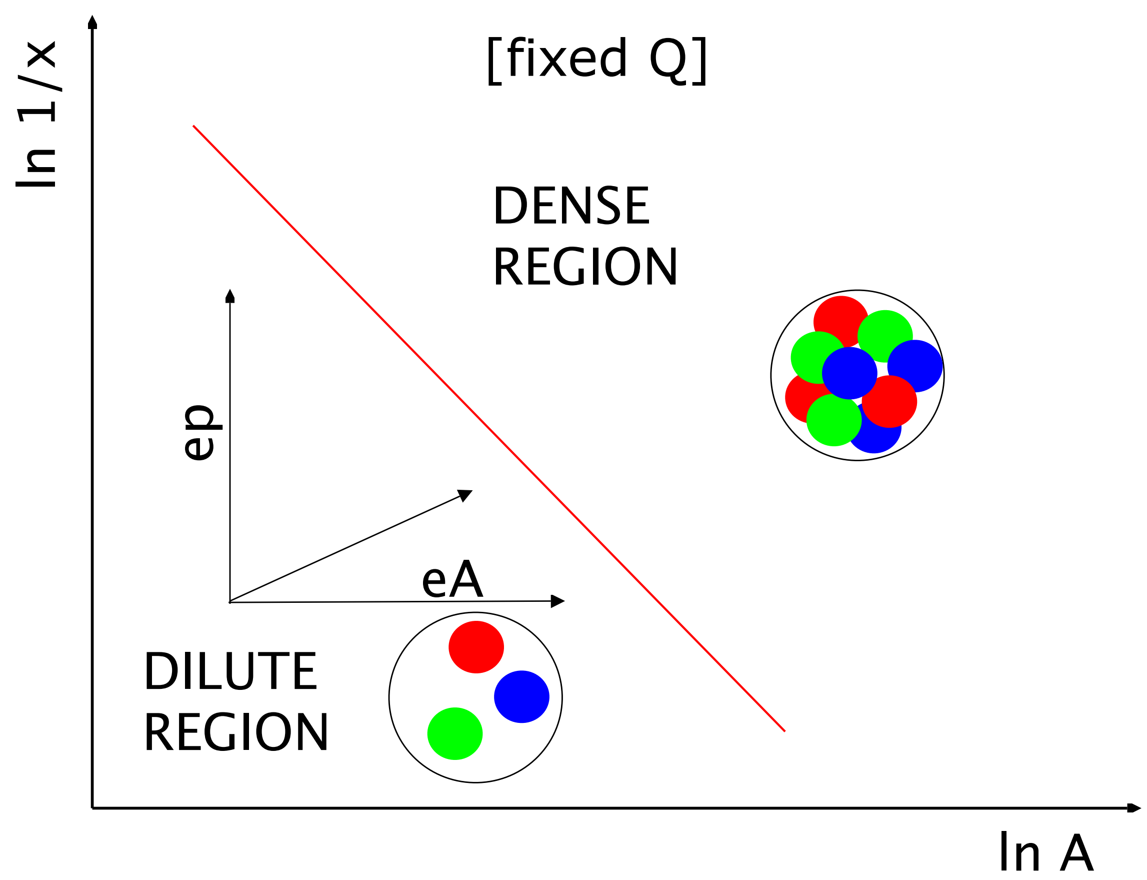
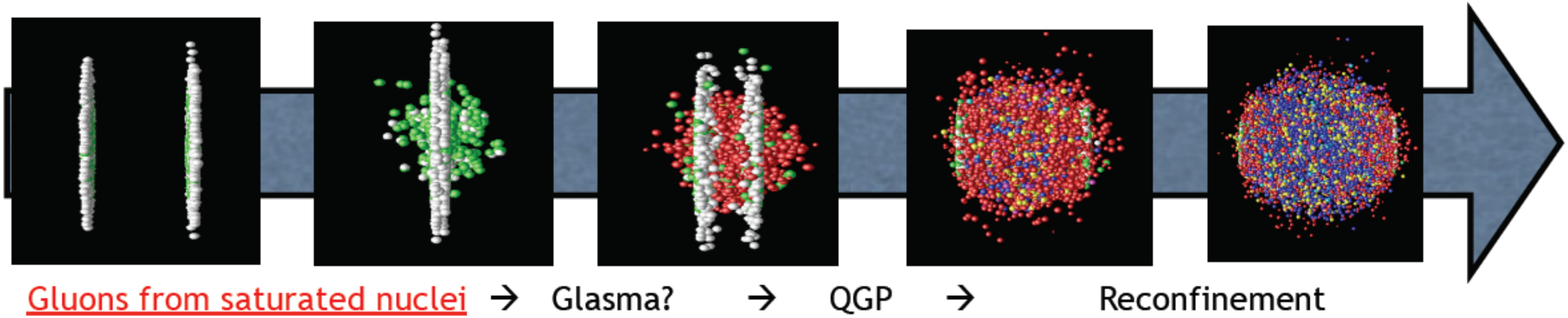
- All approaches eventually have to comply with unitarity constraints ⇒ **non-linear effects** that are density effects.





Relevance for HIC:



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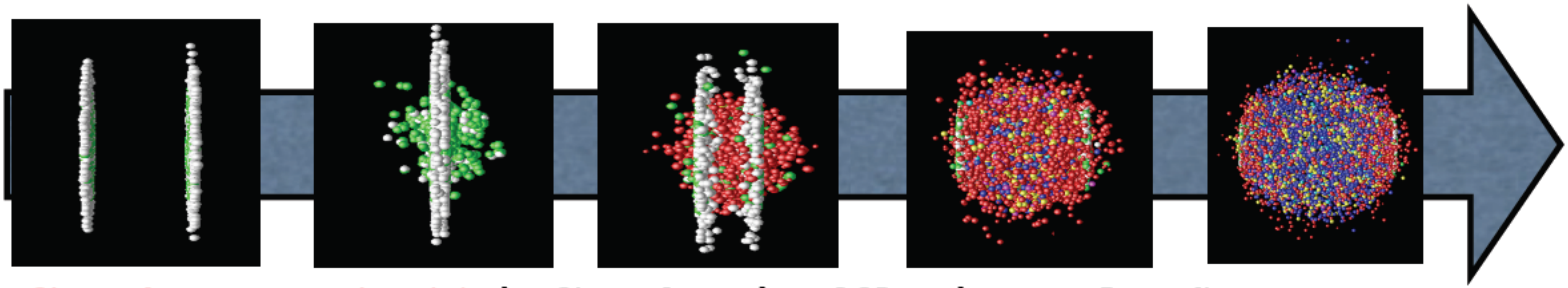

Gluons from saturated nuclei → Glasma? → QGP → Reconfinement

- Nuclear wave function at small x: nuclear structure functions.

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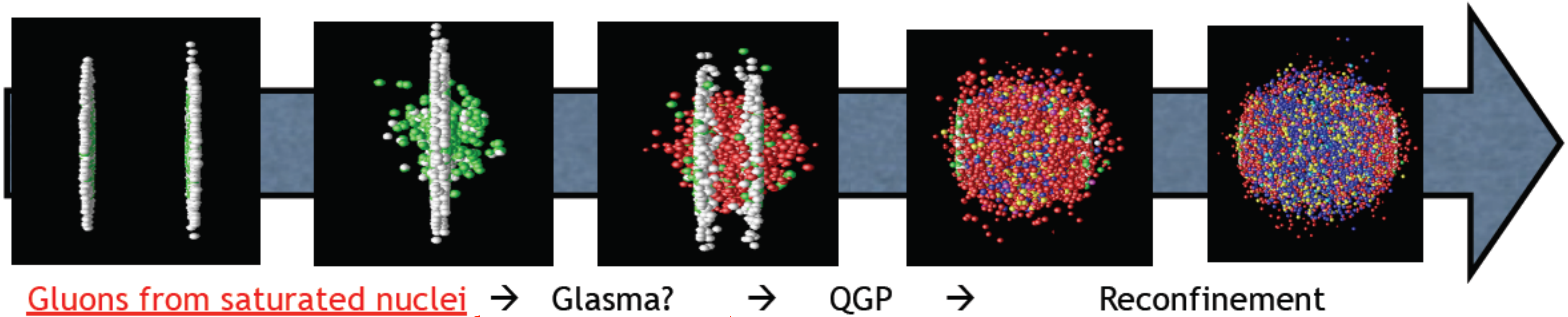

- Nuclear wave function at small x: nuclear structure functions.

- Particle production at the very beginning: which factorisation in eA?

- How does the system behave as ~ isotropised so fast?: initial conditions for plasma formation to be studied in eA.

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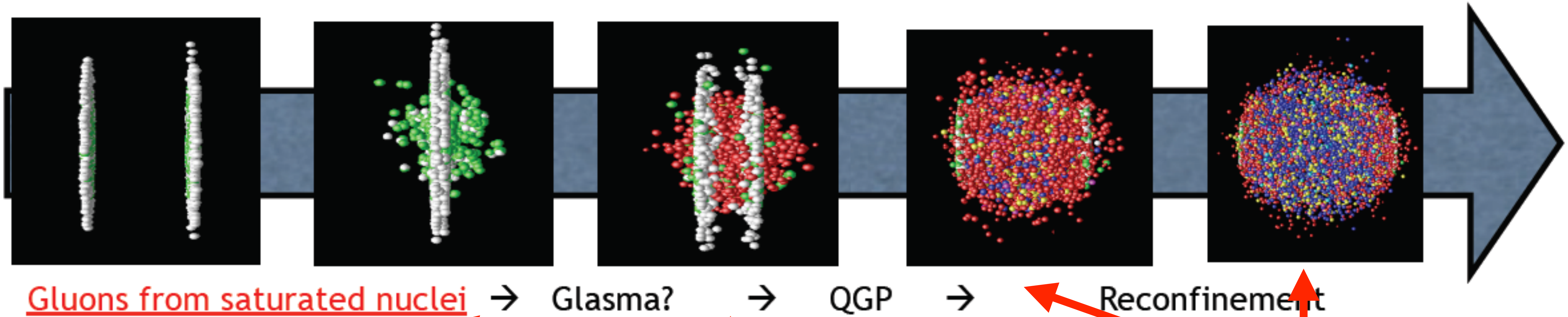

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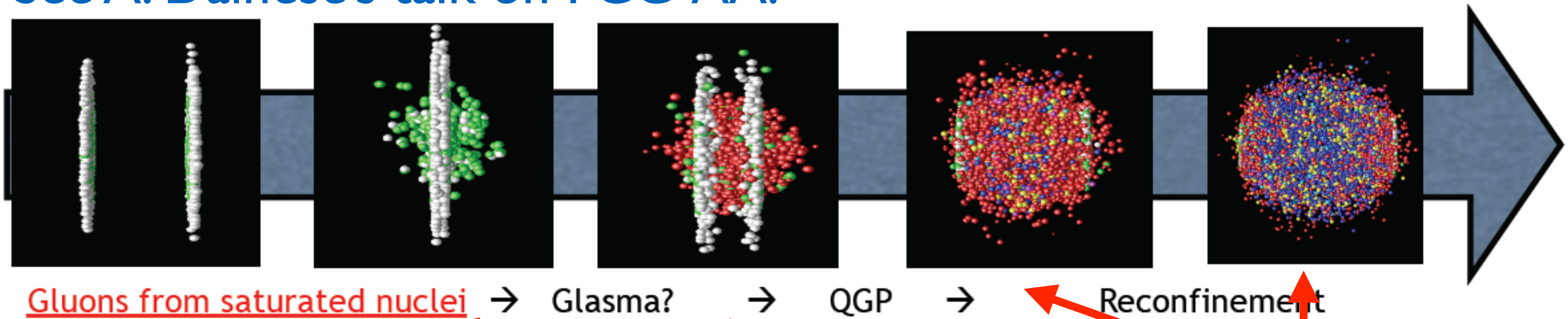
Relevance for HIC:

See A. Dainese's talk on FCC-AA.



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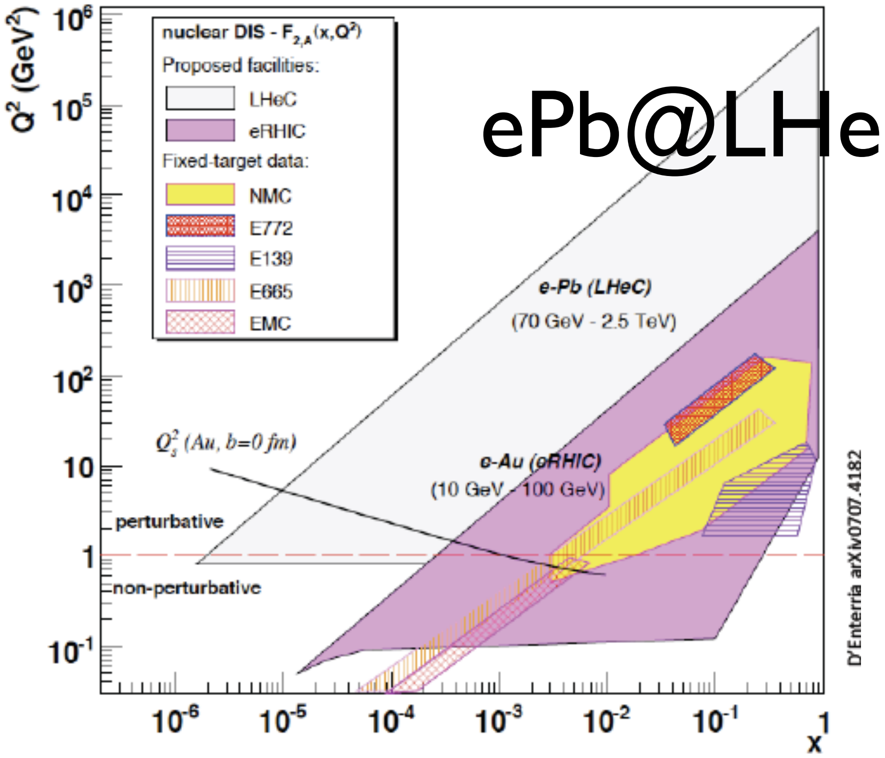
Kinematic plane:

ePb@LHeC



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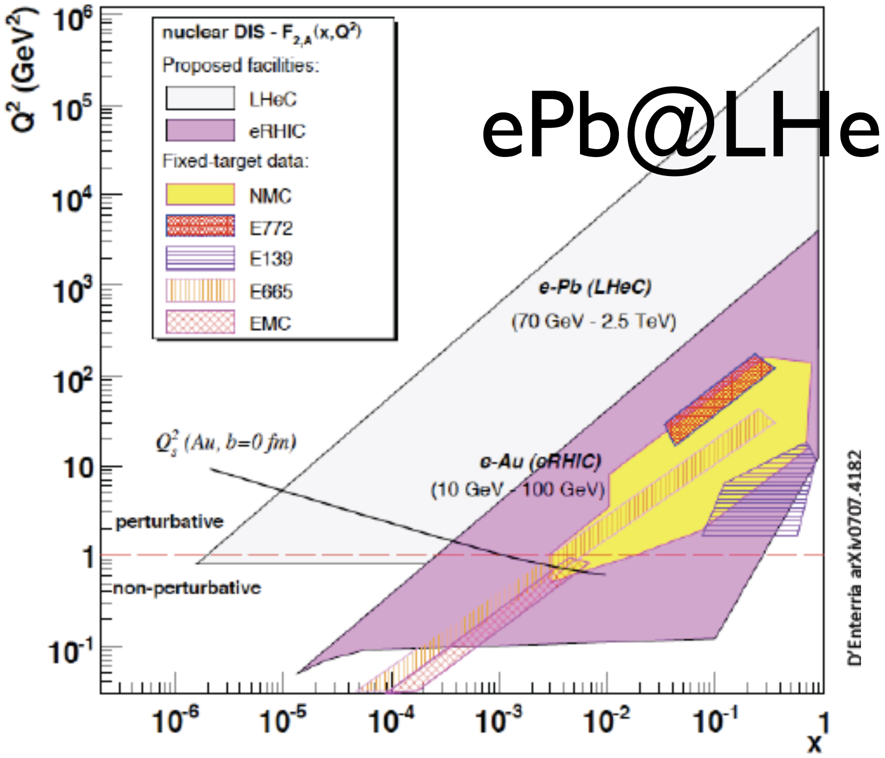

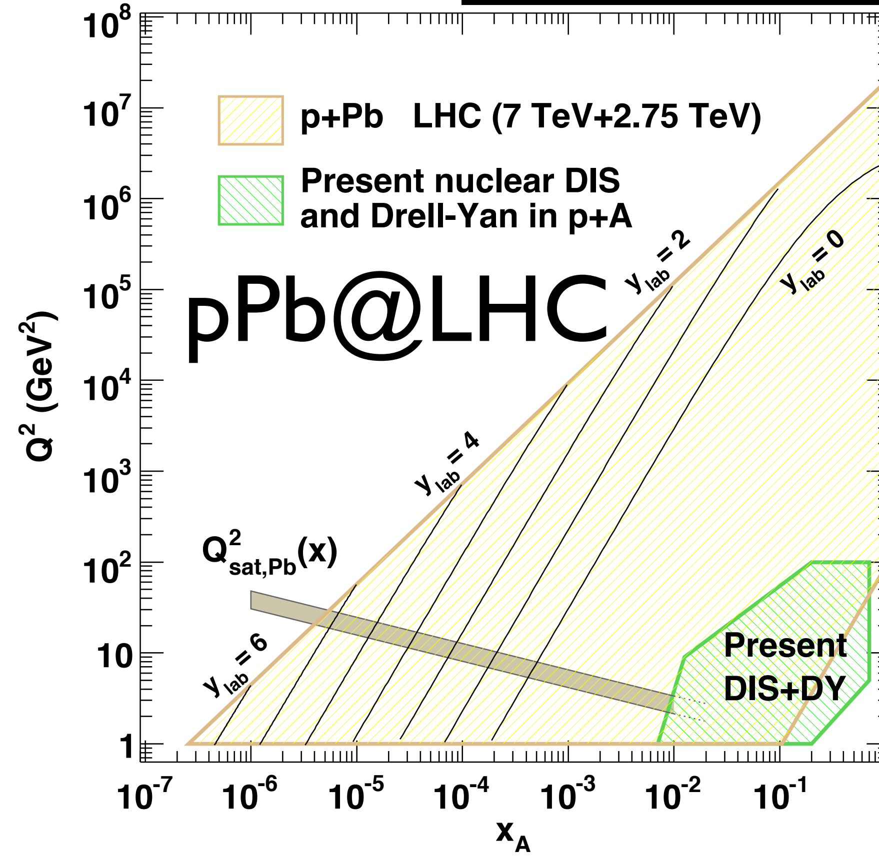

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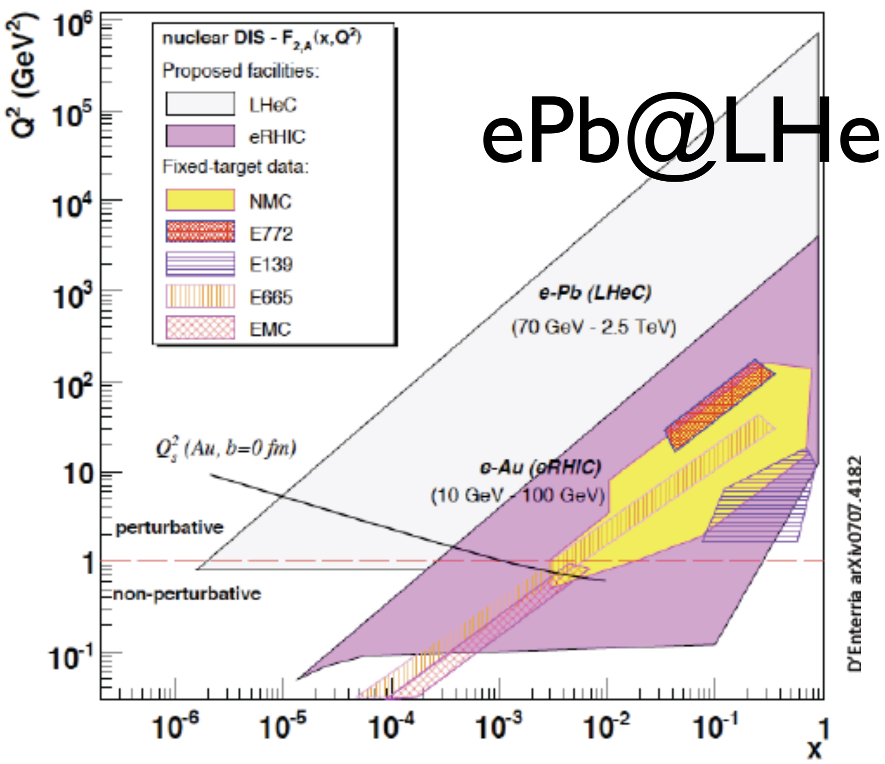

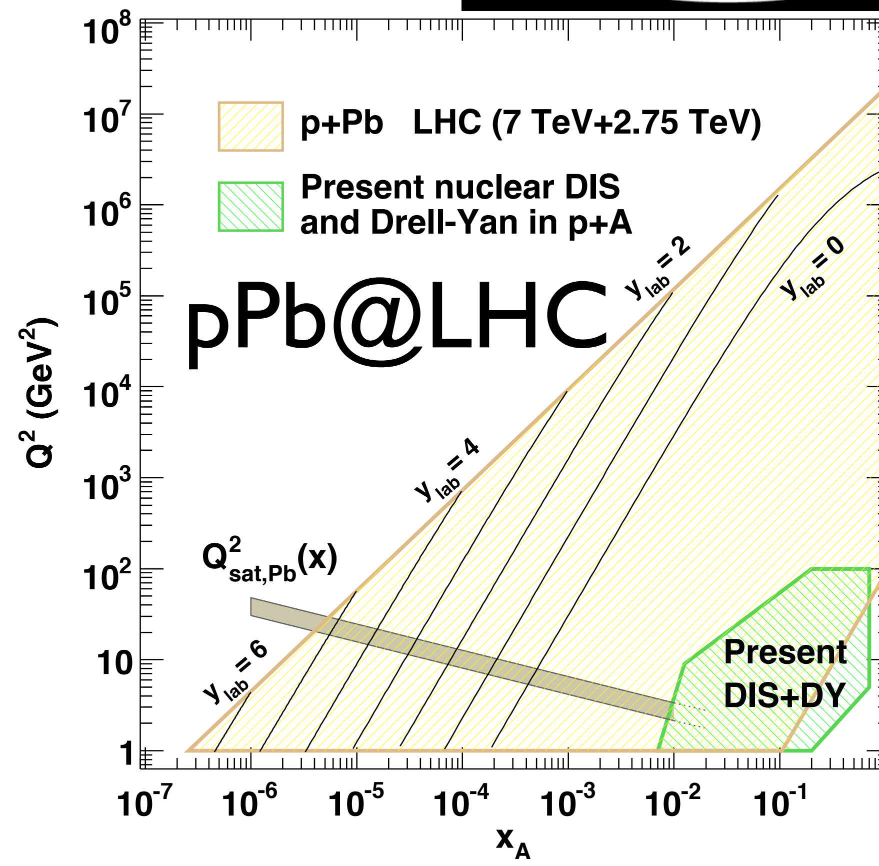

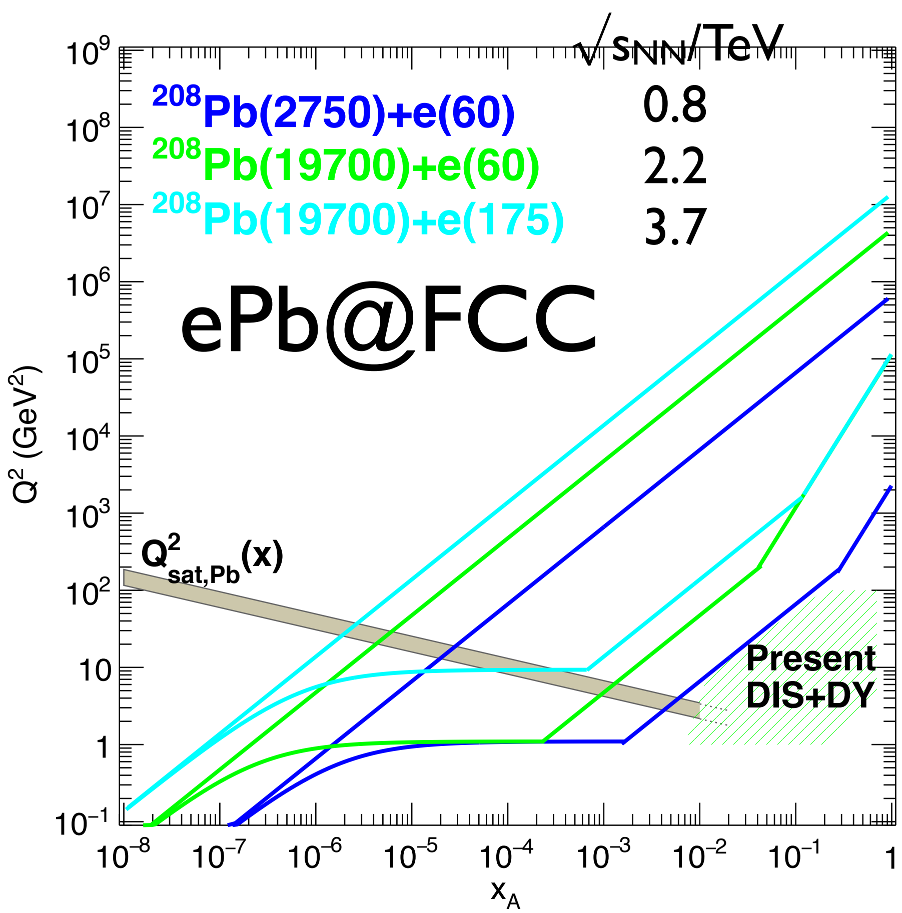

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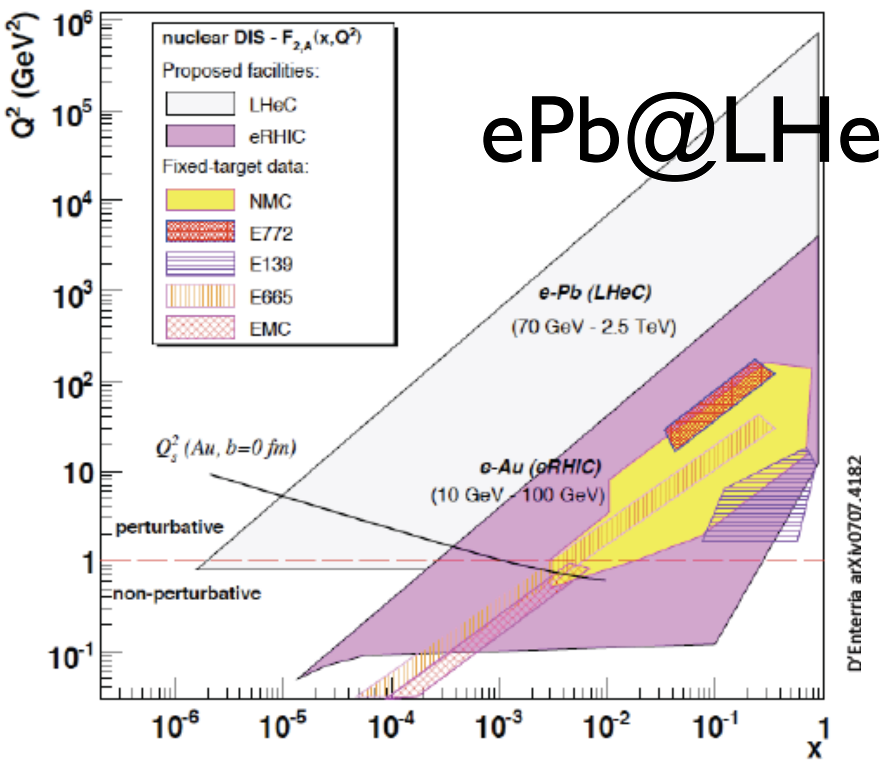

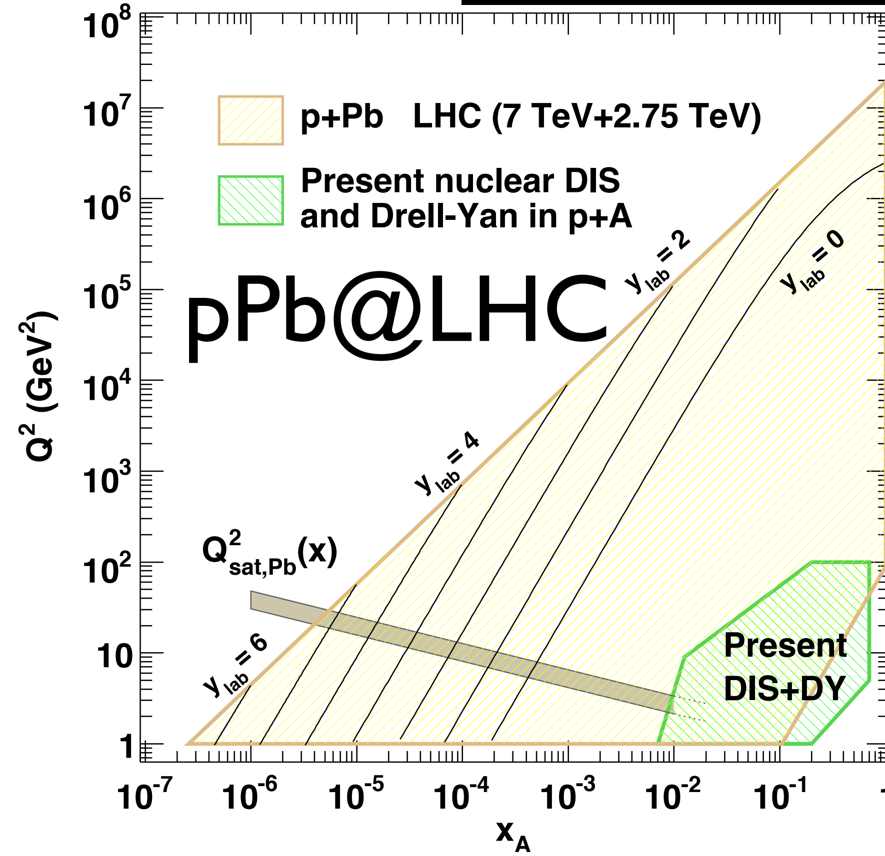

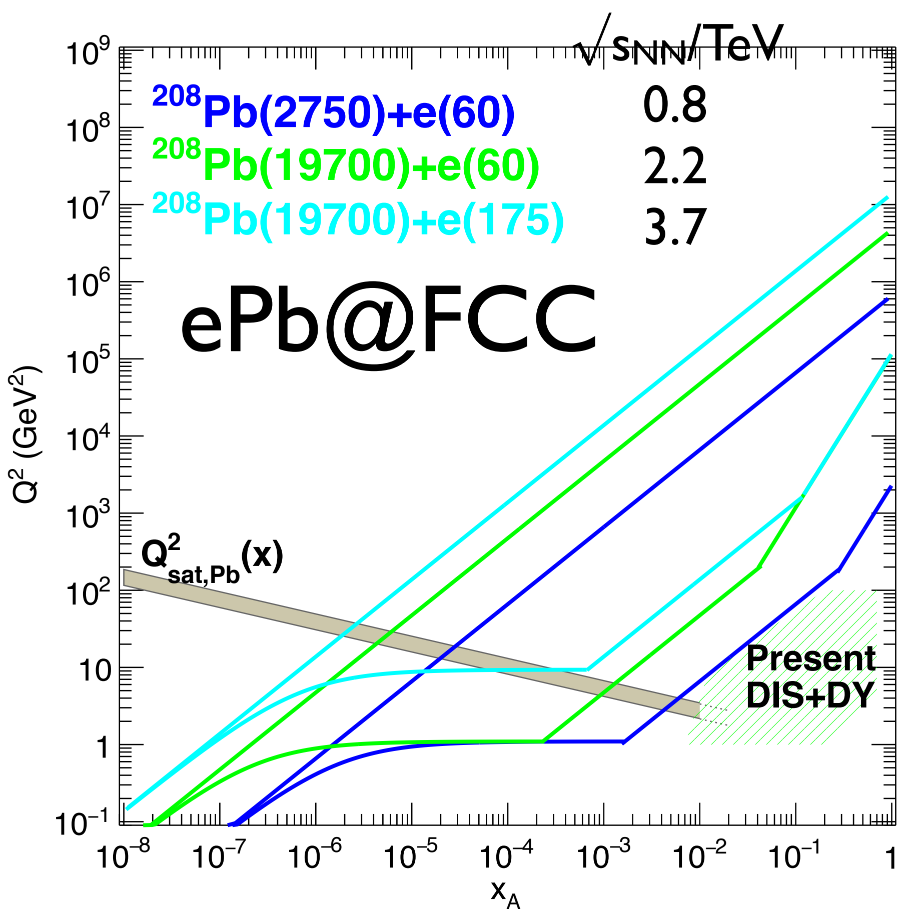

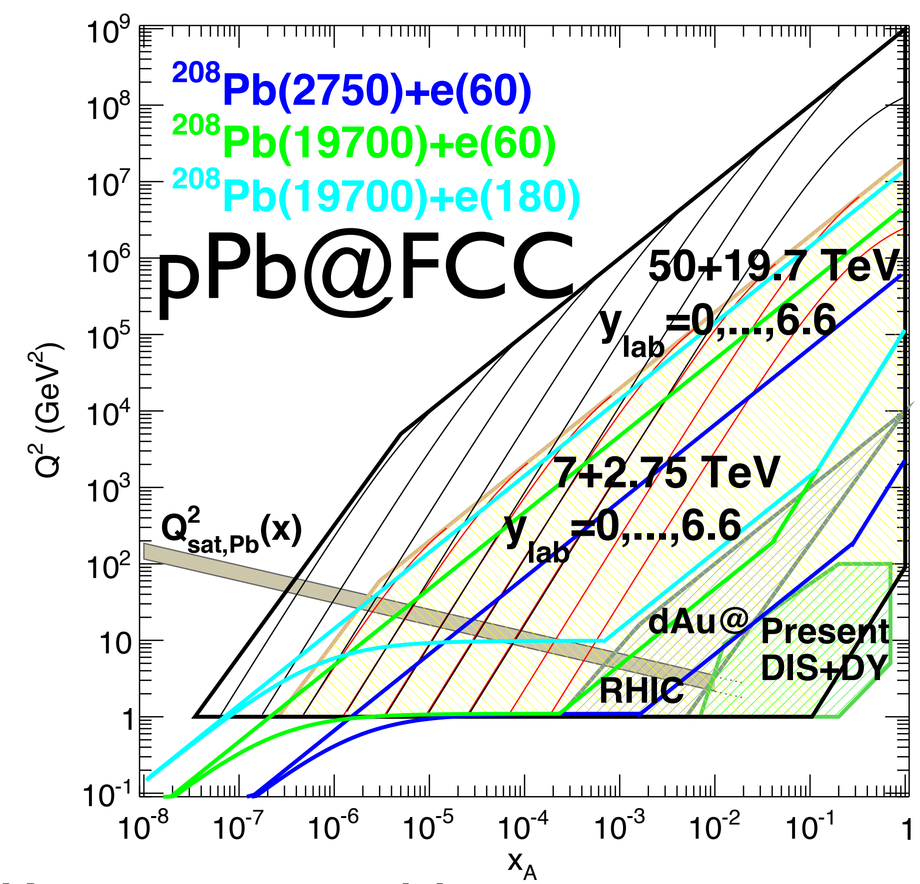

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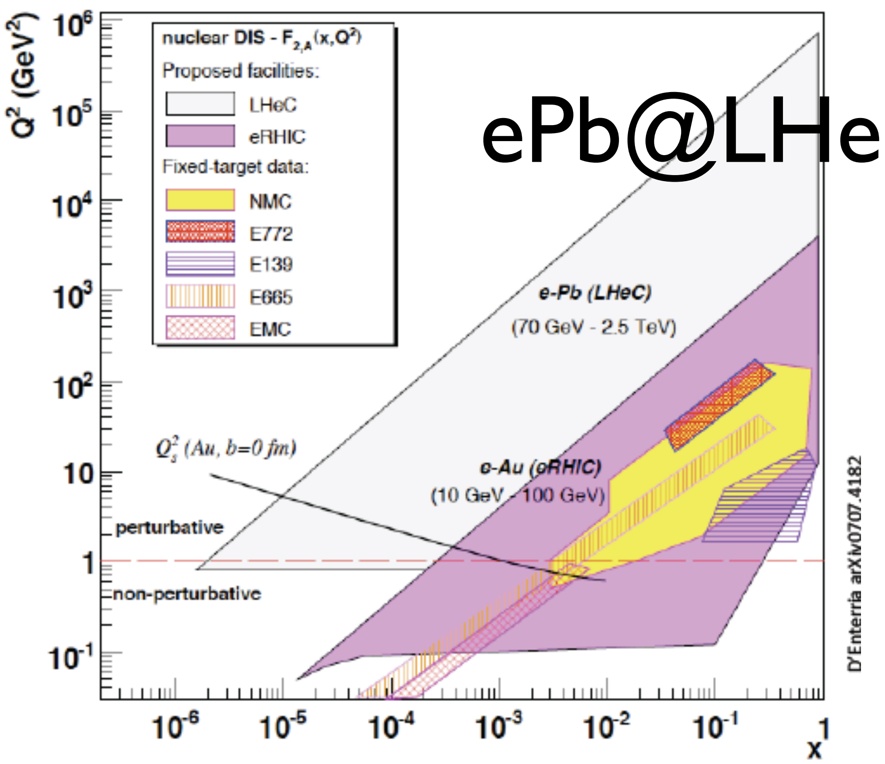
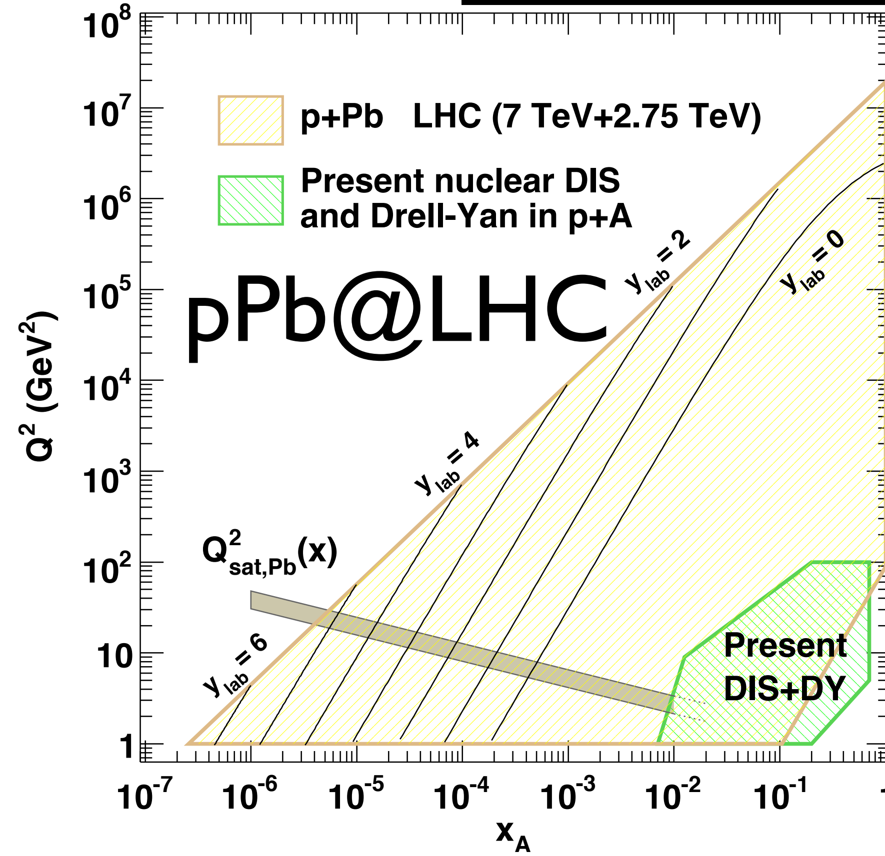
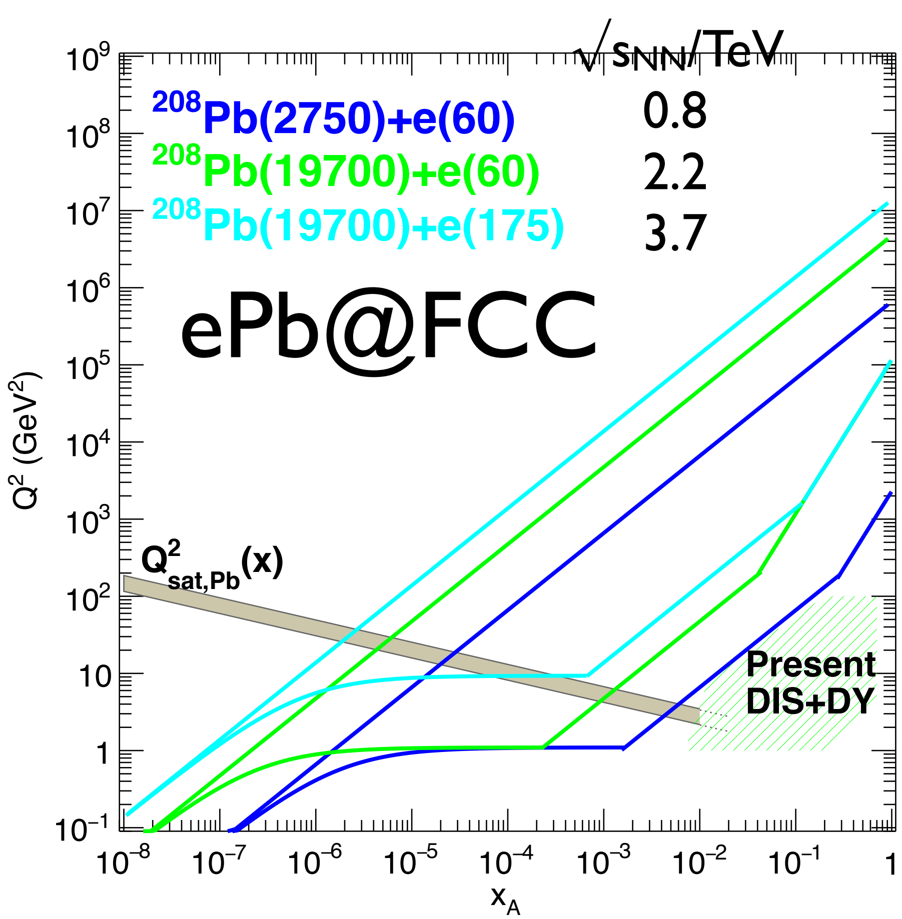
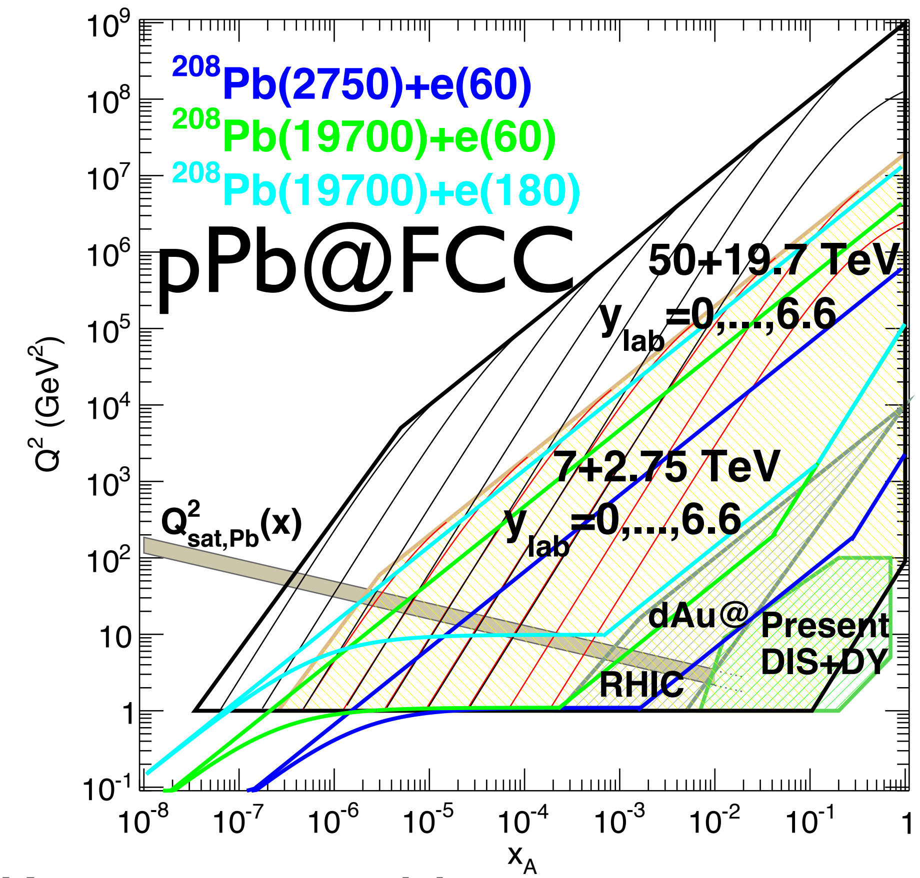




- Kinematic planes overlapping with the corresponding hh colliders:
  ➜ in a cleaner experimental setup;
  ➜ on firmer theoretical grounds.





Luminosity:

- Nominal case: 60 GeV electron beam against the hadron beams.

ep (03.16):

Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
$\sqrt{s}$ [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [10^{33}cm^{-2}s^{-1}]	1.3	10.1	15.1	9.2

- For the LHeC ($N_{Pb}=7\times10^7$/bunch - '12 values) ⇒ ~0.1 fb^{-1}/month.

$$L_{eN} = \begin{cases} 9\times10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Nominal Pb)} \\ 1.6\times10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} & \text{(Ultimate Pb)} \end{cases}$$

eD: $L_{eN} \gtrsim 3\times10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

(Pb numbers ~ 3 times higher with updated Pb parameters).

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- Crude estimates: for the FCC-he ($N_{Pb}=2\times10^8$/bunch - '16 values) and rescaling hadron parameters only, we get $L_{eN}=3\times10^{33}$ cm^{-2}s^{-1} ⇒ ~ 4 fb^{-1}/month (J. Jowett). [Goal of PbPb@HL-LHC ~ 0.4 fb^{-1}/exp.]

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nPDFs at the LHC:

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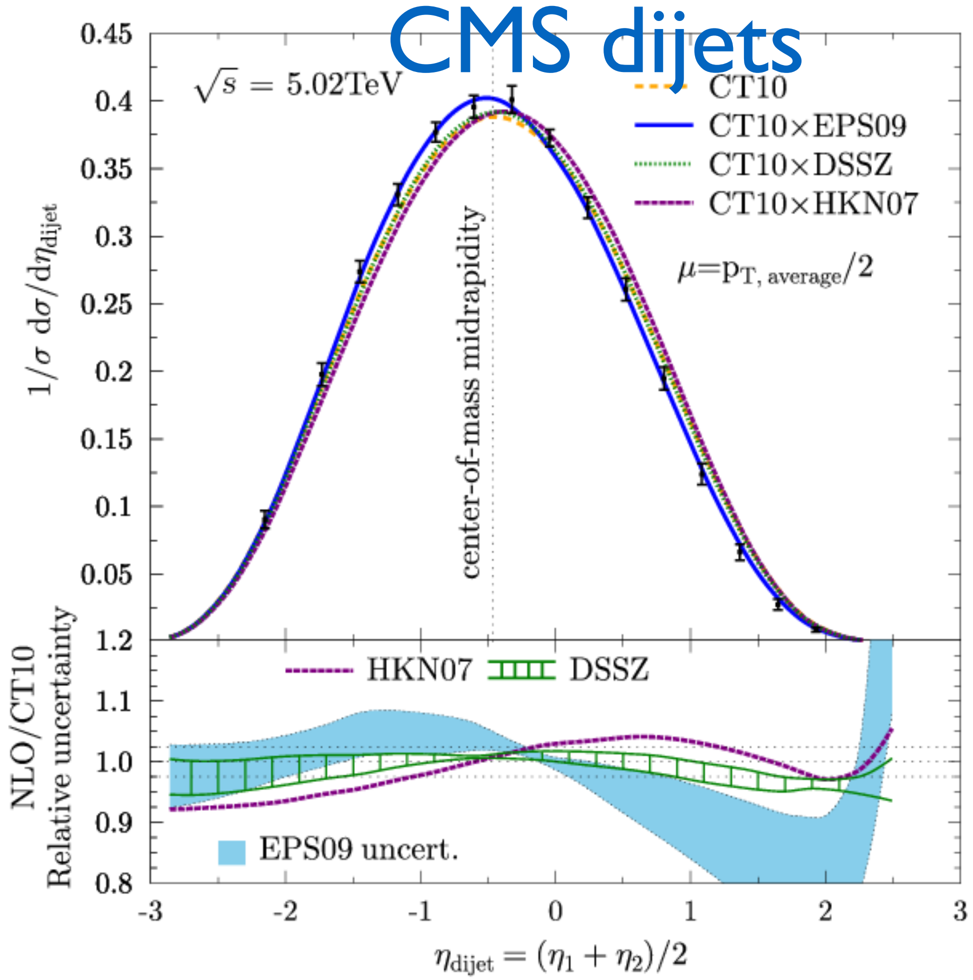
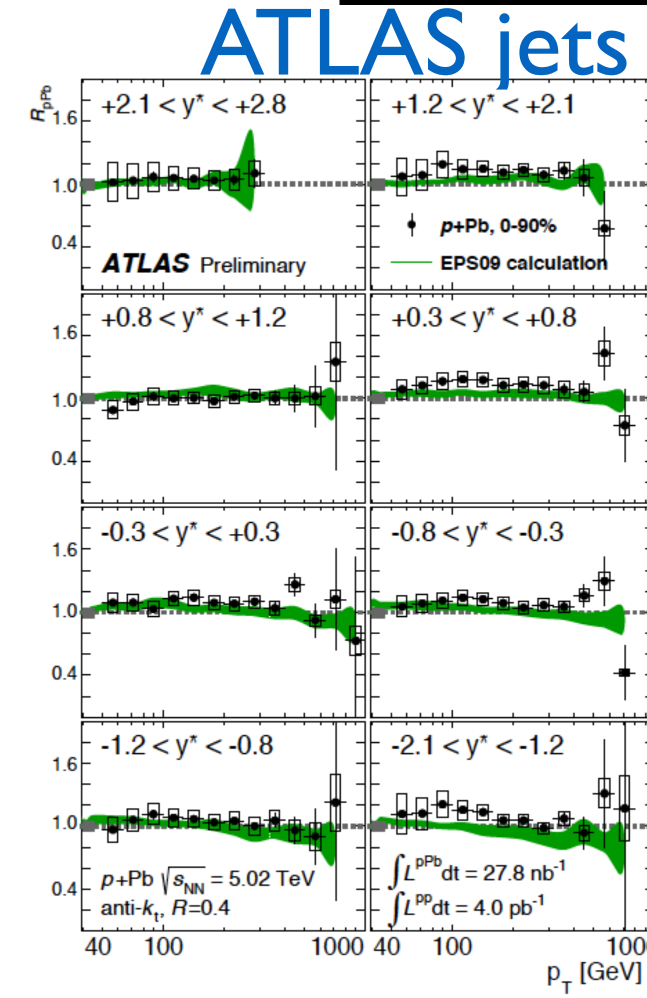
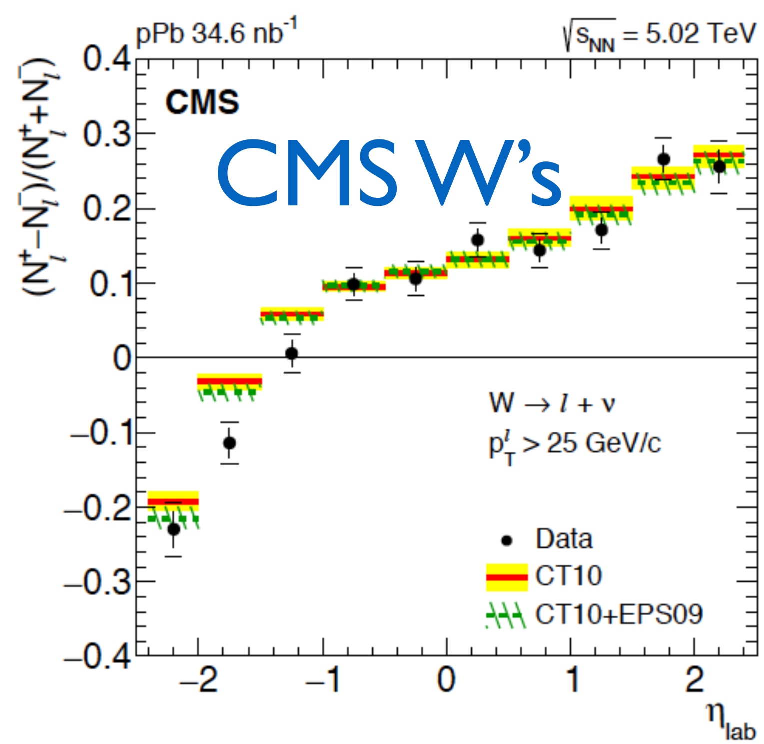
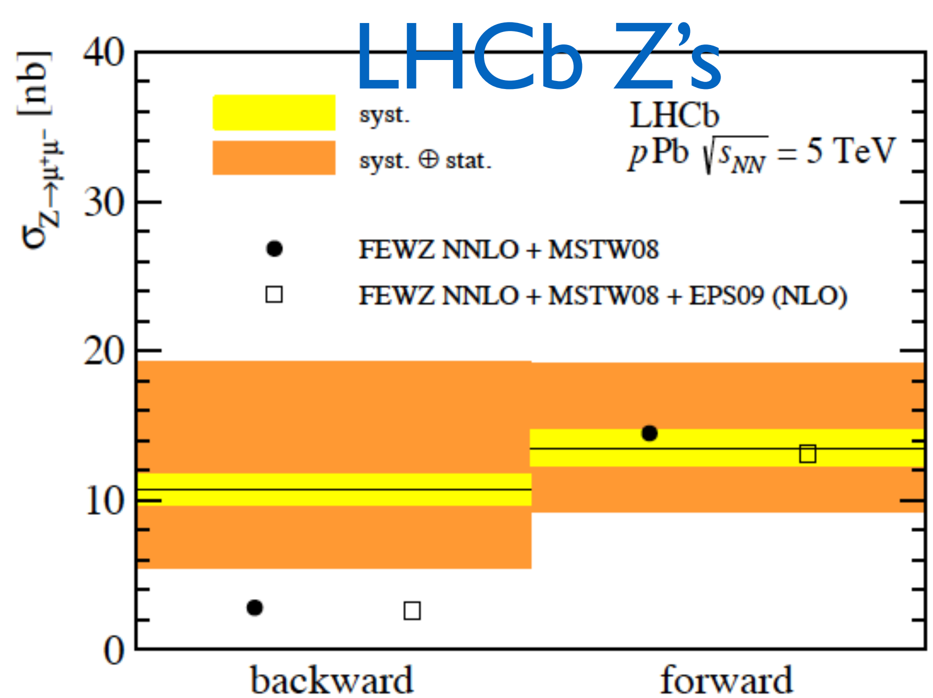
- No sizeable in-medium effects e.g. energy loss, but delicate centrality issues!!!









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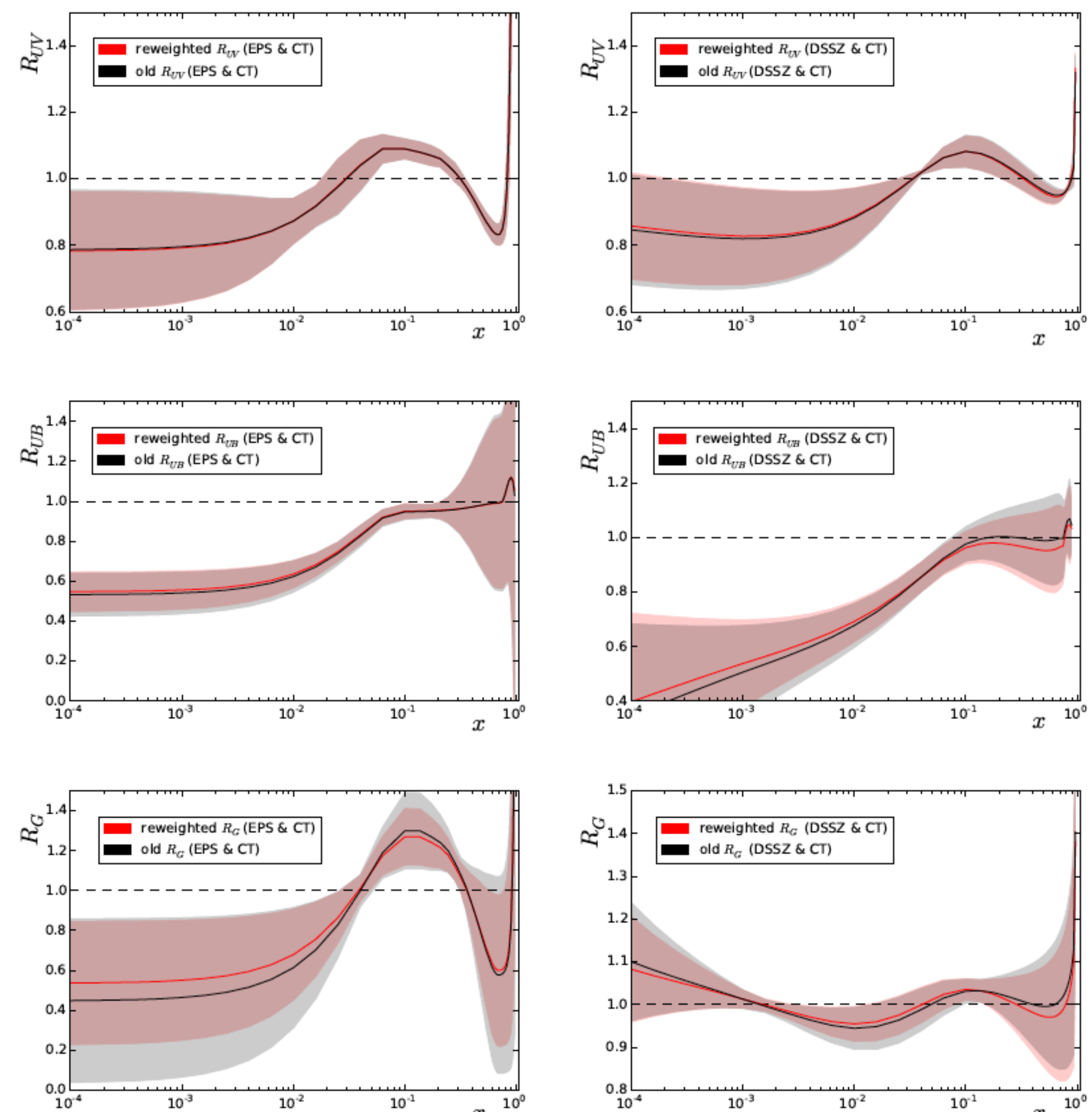
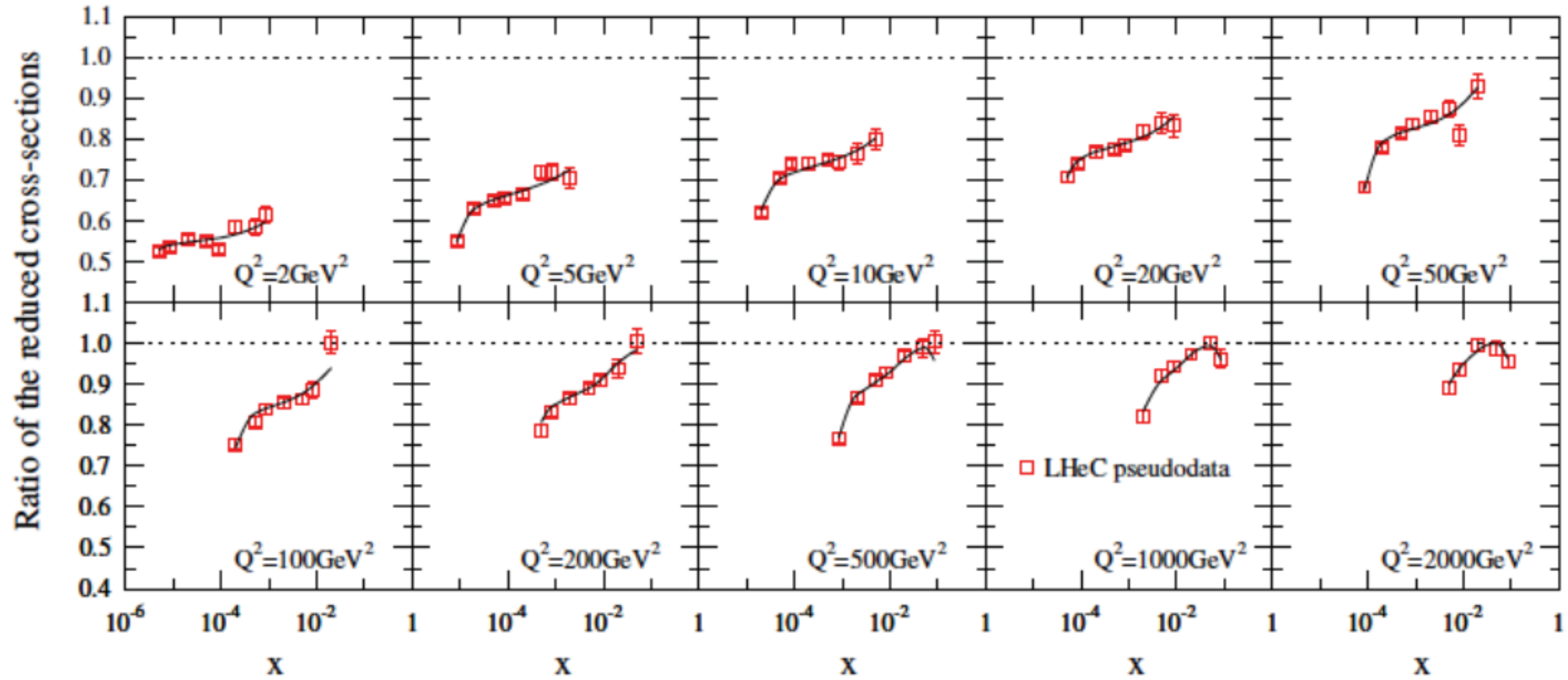
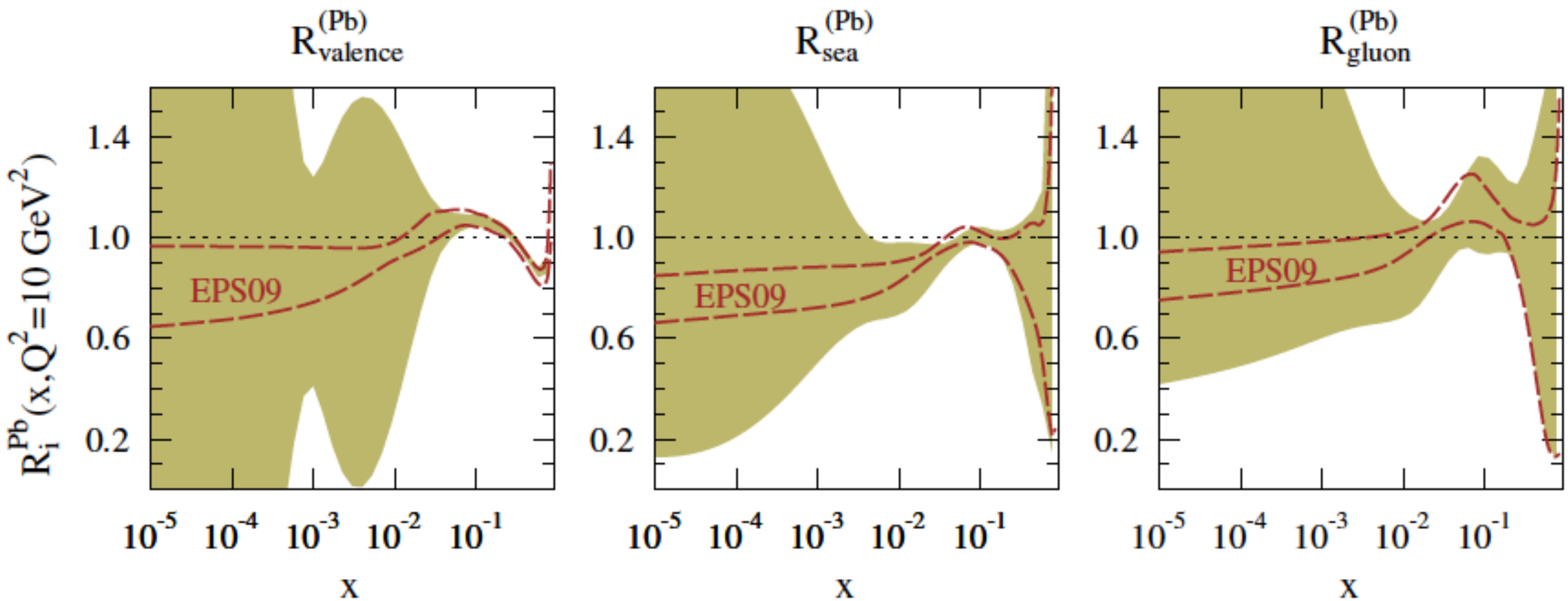
- An analysis of pPb data at 5.02 TeV/nucleon (1512.01528) shows modest constraints of existing data (jets, dijets, EW bosons and charged hadrons) on existing sets of nPDFs and the effects of parametrisation biases.
- EW bosons will allow initial conditions $R_u \neq R_d$.
- nPDF linked with PDF.



nPDFs at the LHeC:

- Large impact on nPDFs, possible to make a Pb fit without proton PDFs!!!
- Large room for improvements: NC+CC at several energies, flavour decomposition,…





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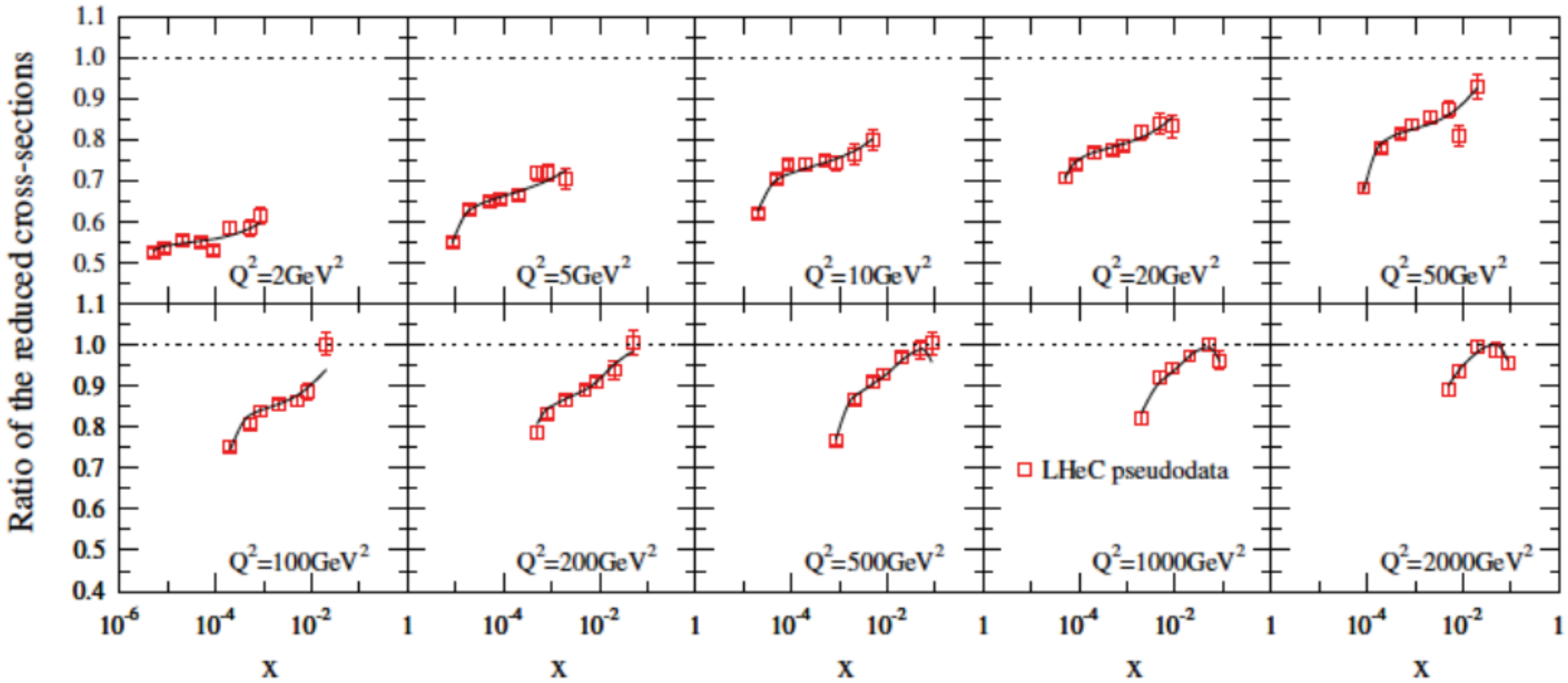
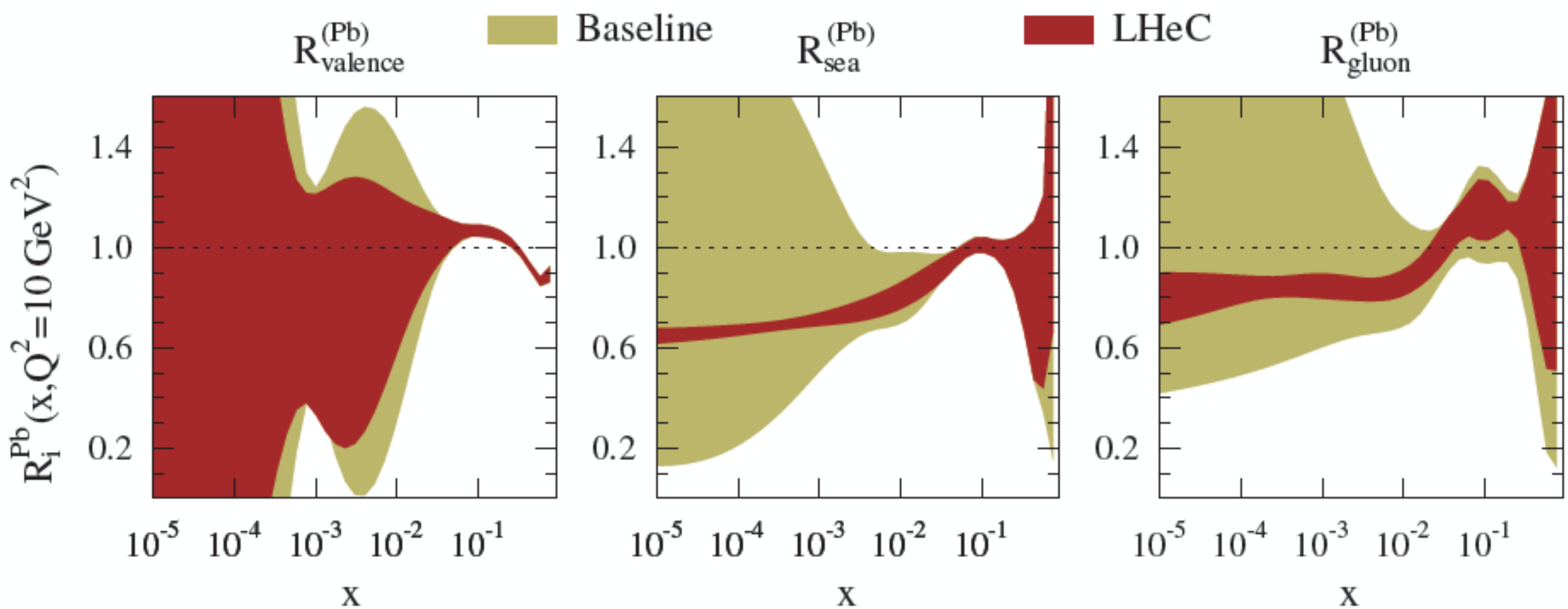
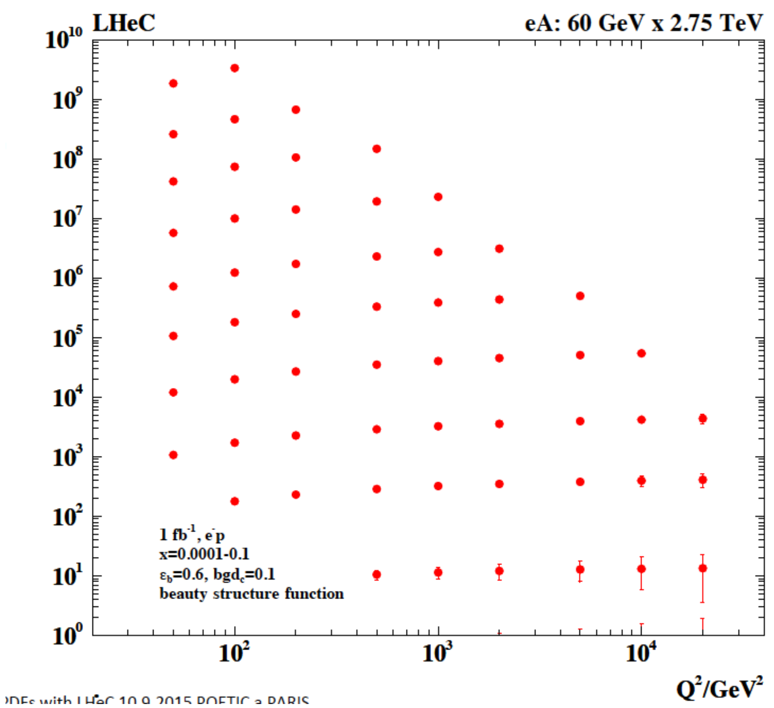




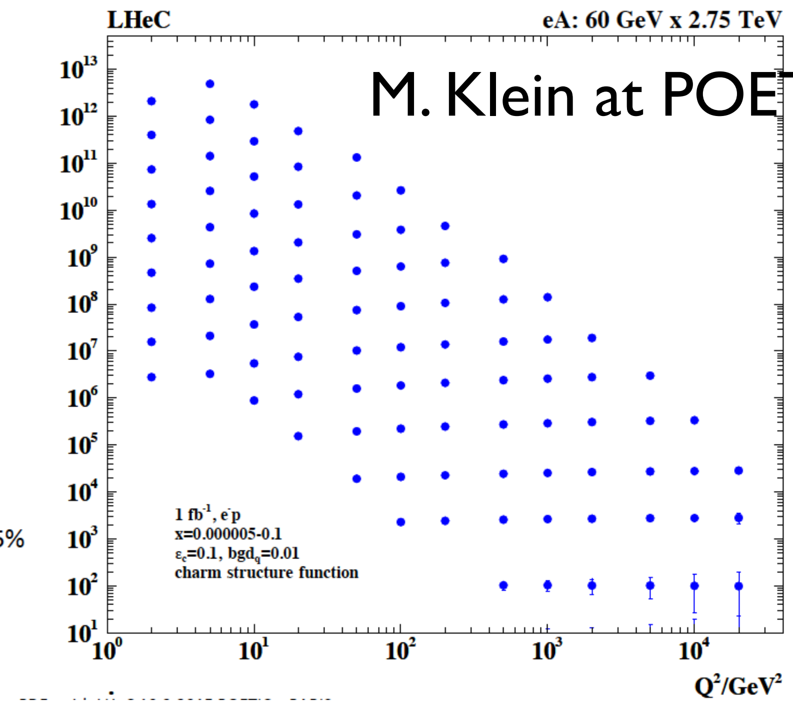
nPDFs at the LHeC:

Heavy Flavour – Beauty in ePb - from NC



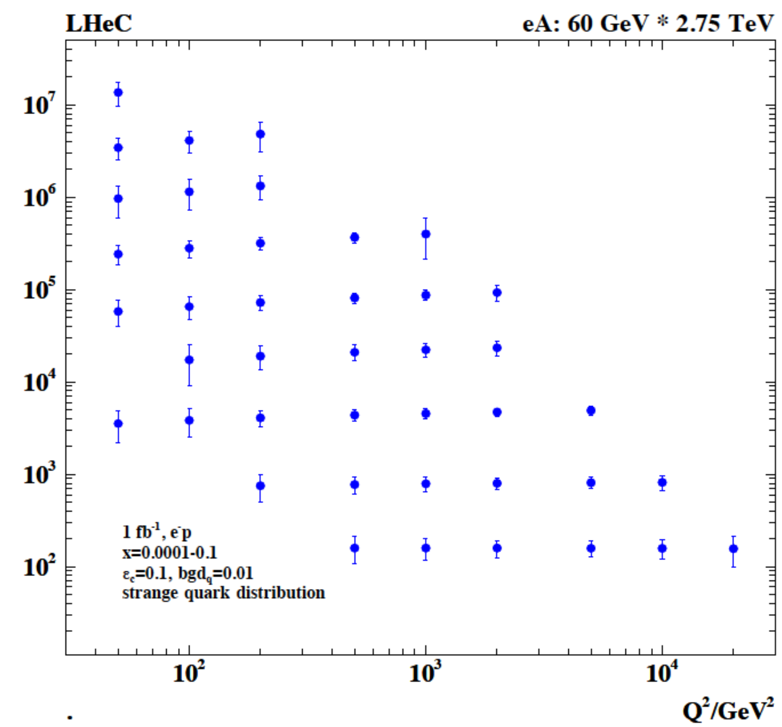
3-5%

Heavy Flavour – Charm in eA - from NC

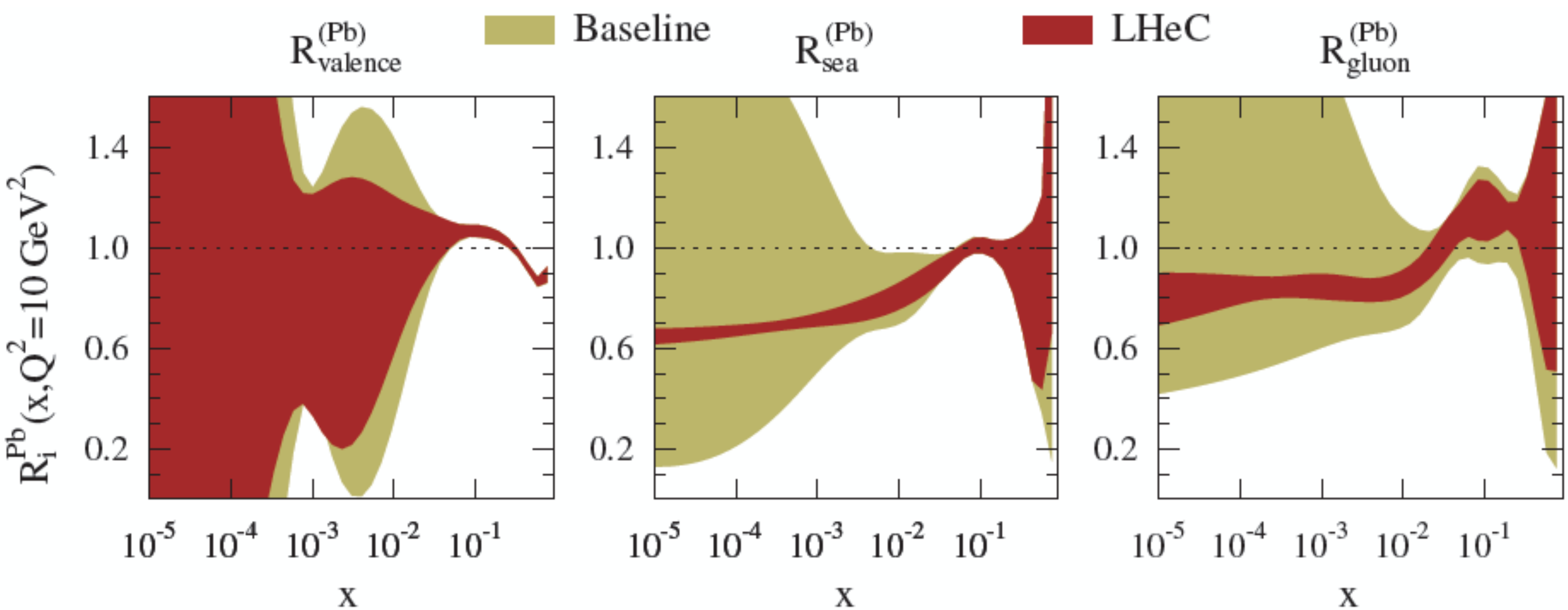


3-5%

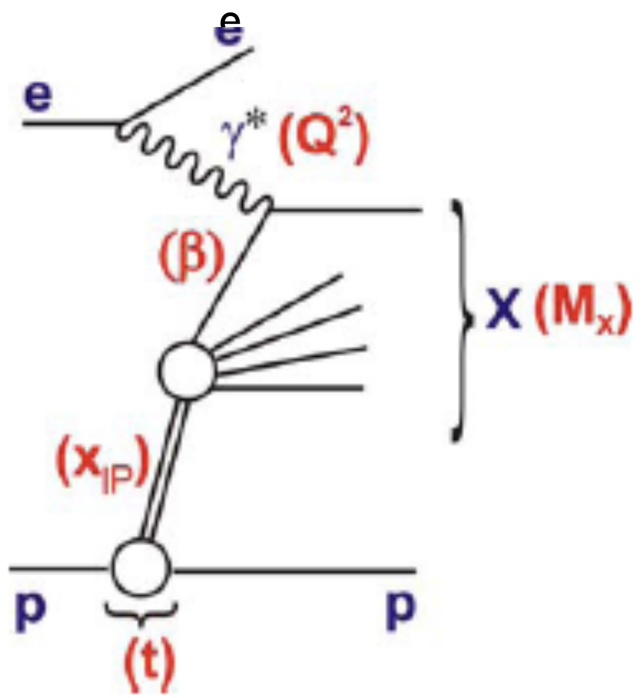
Heavy Flavour – Strange in ePb - from CC

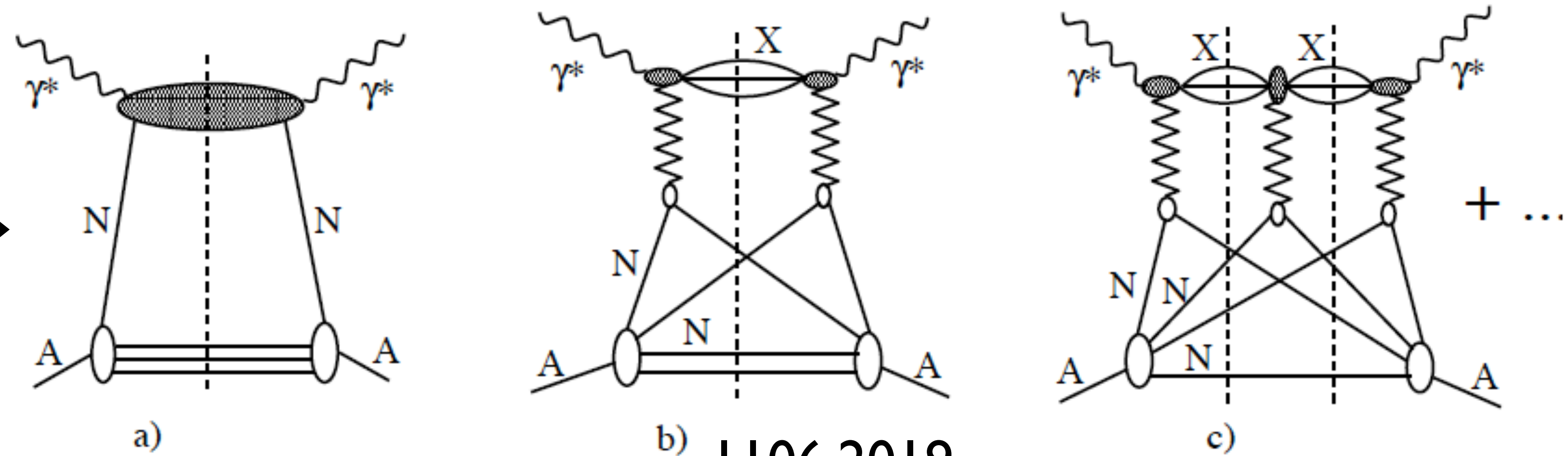


10-20



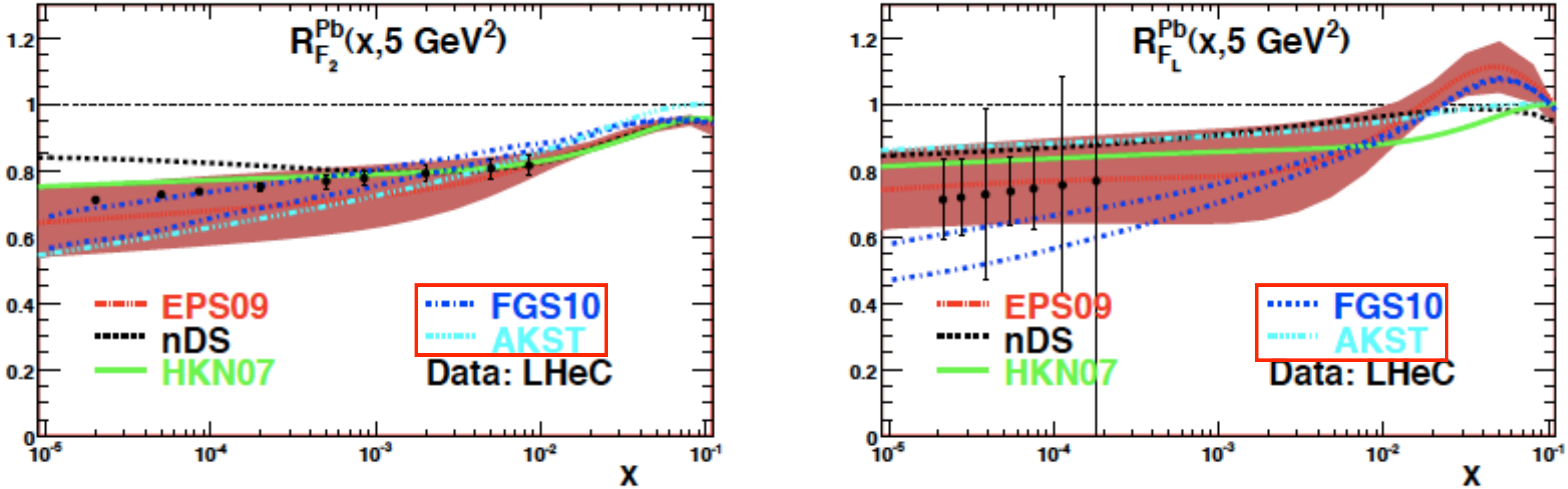
Diffraction & shadowing:





1106.2019

- Diffraction is linked to nuclear shadowing through basic QFT (Gribov): eD to test and set the 'benchmark' for new effects.



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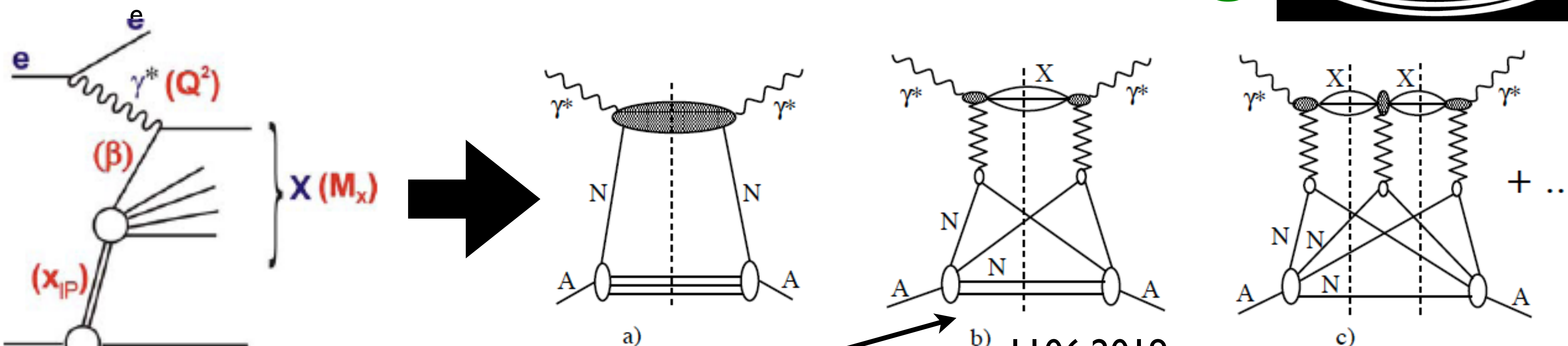

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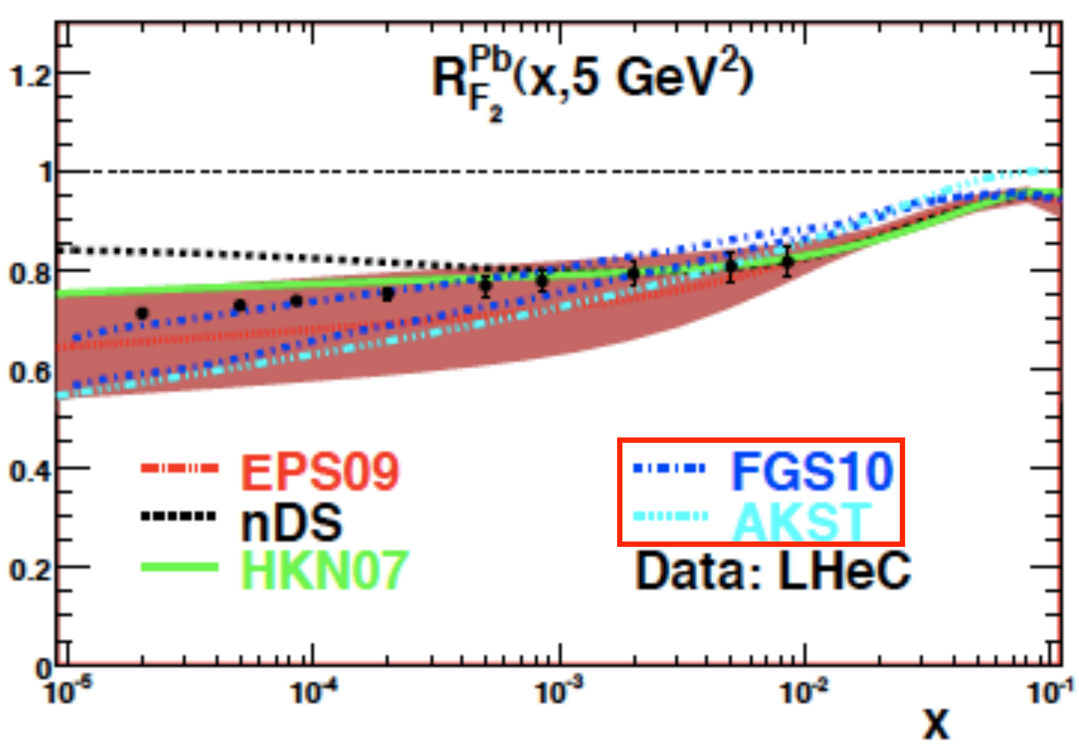
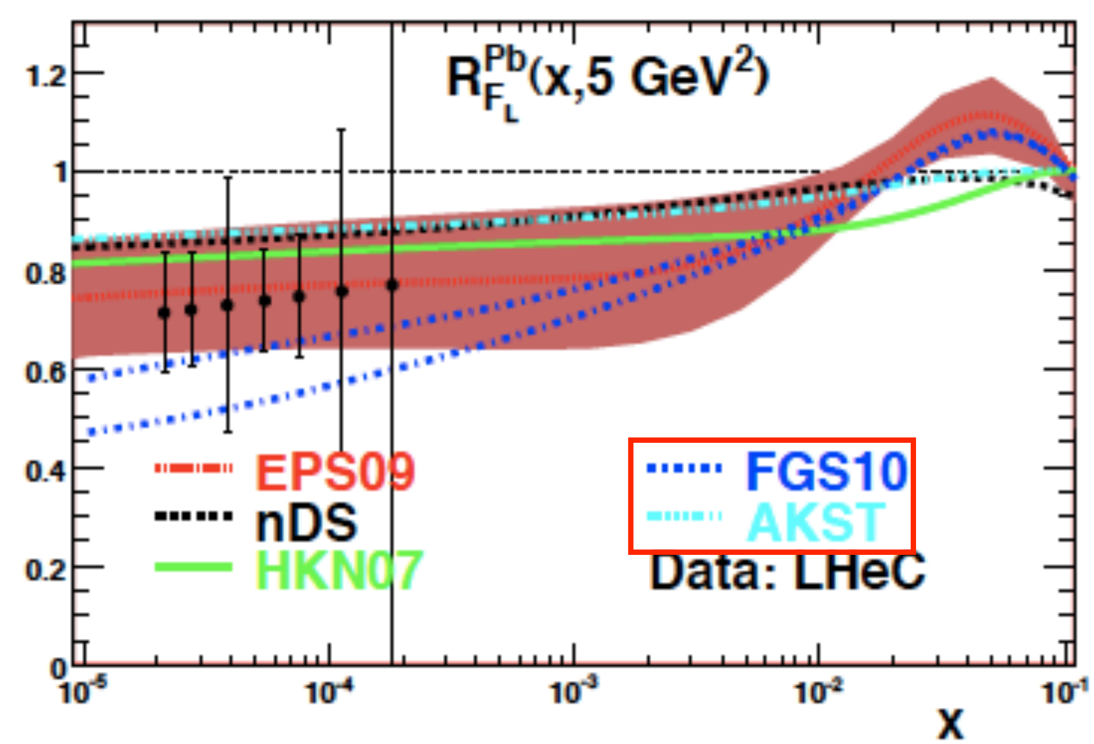
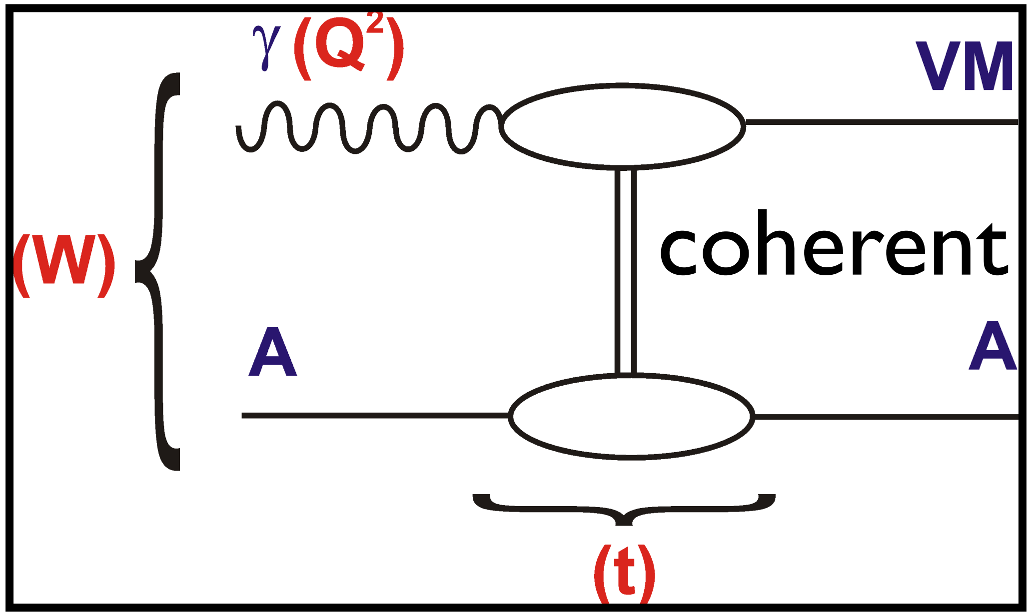


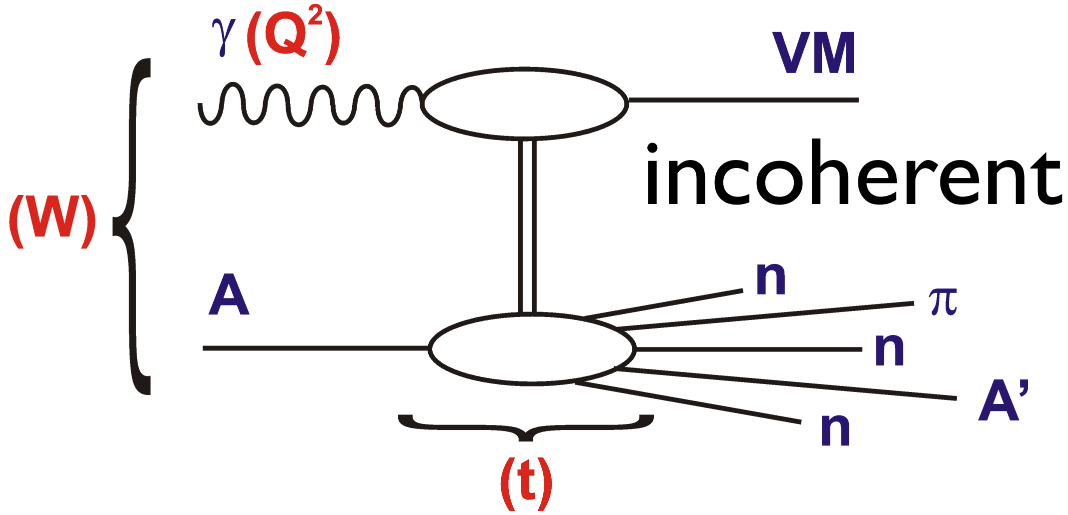


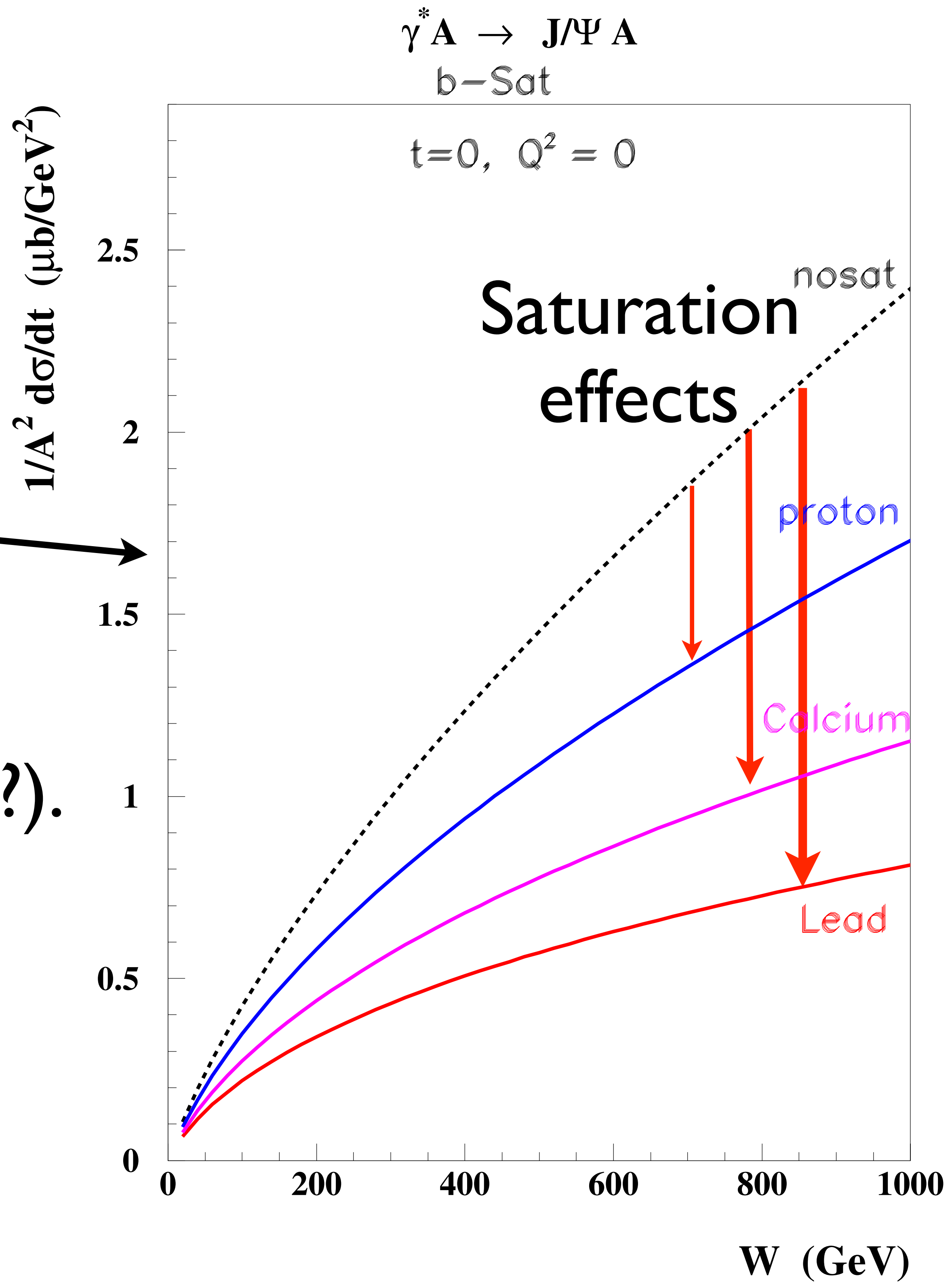
Elastic VM production:



- For the coherent case, predictions available.

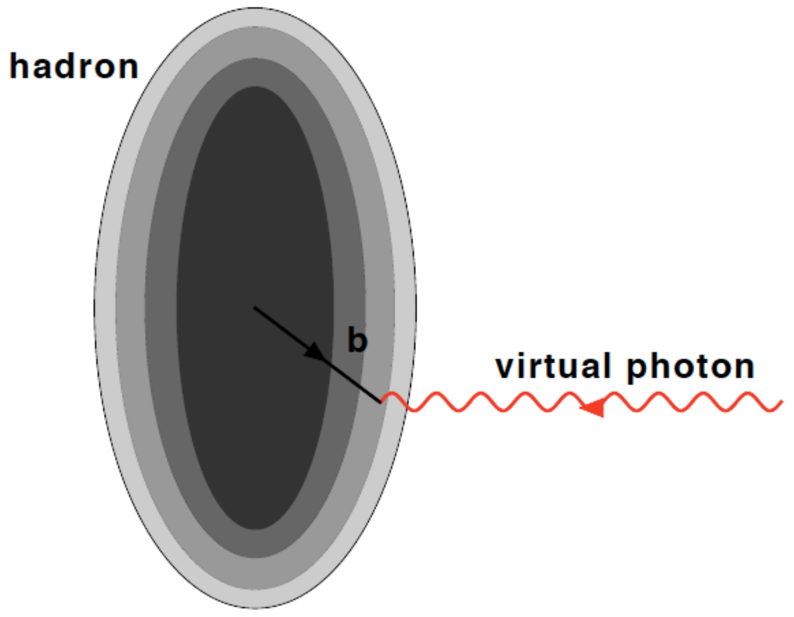
- Challenging experimental problem (neutron tagging in ZDC?).

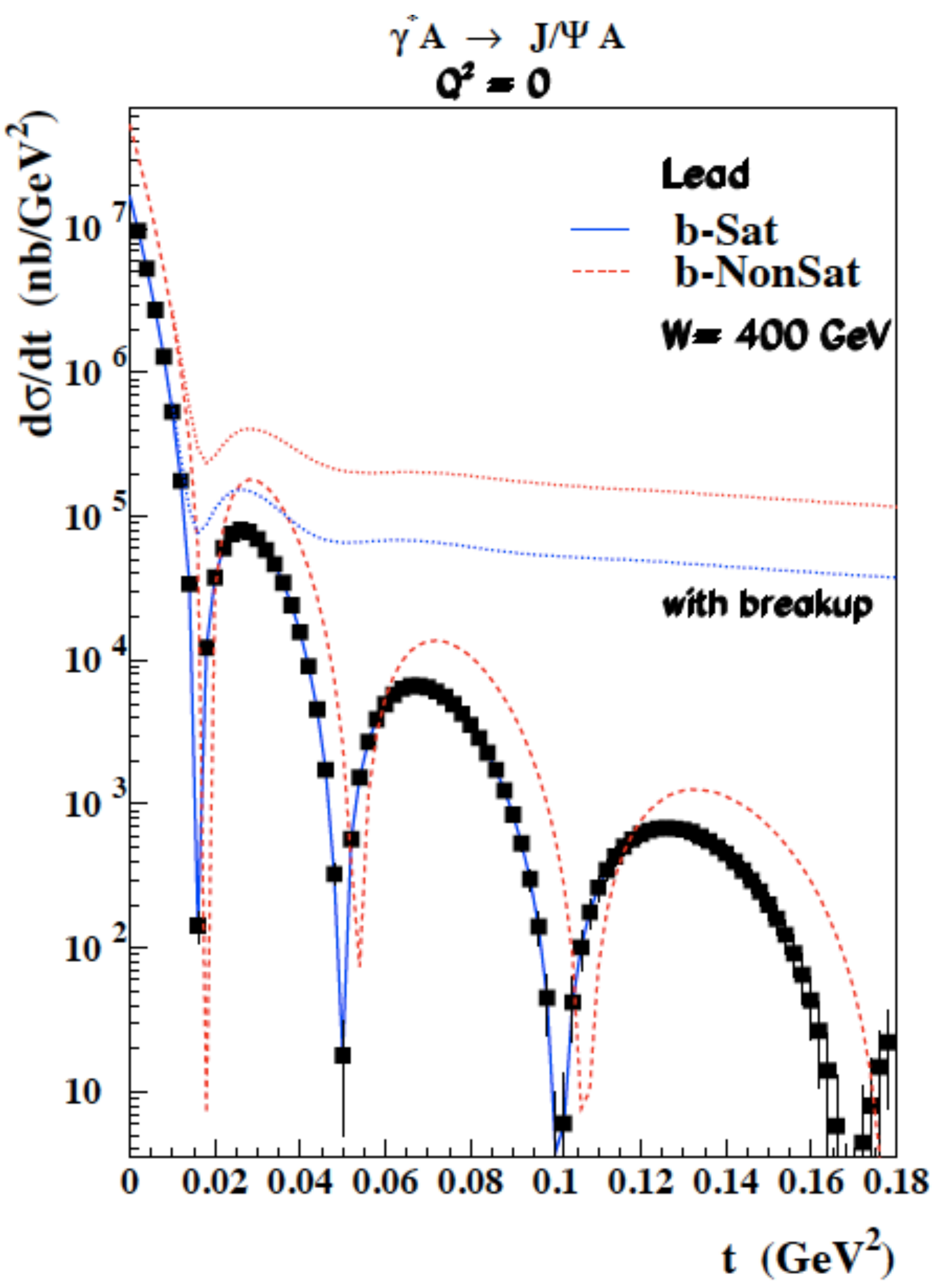




Transverse scan:

- t-differential measurements give a gluon tranverse mapping of the hadron/nucleus: gluon GPDs.





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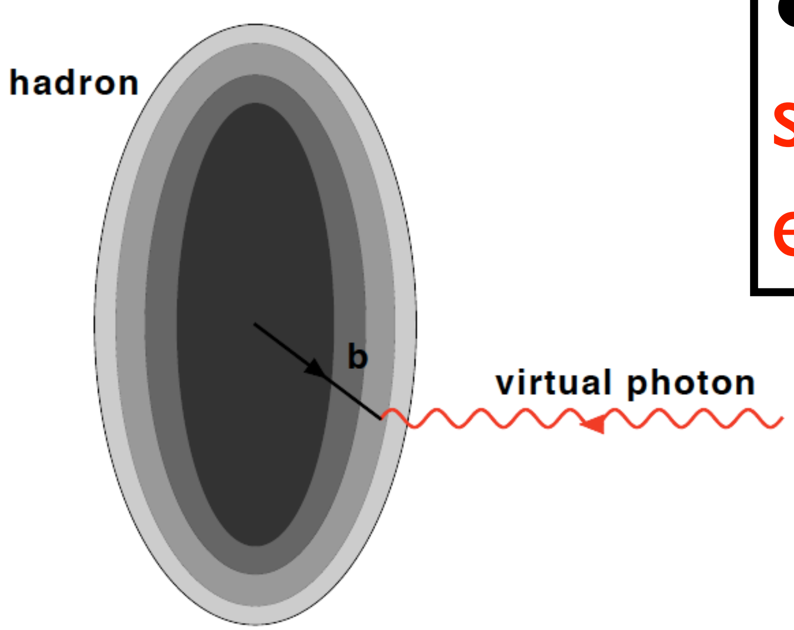
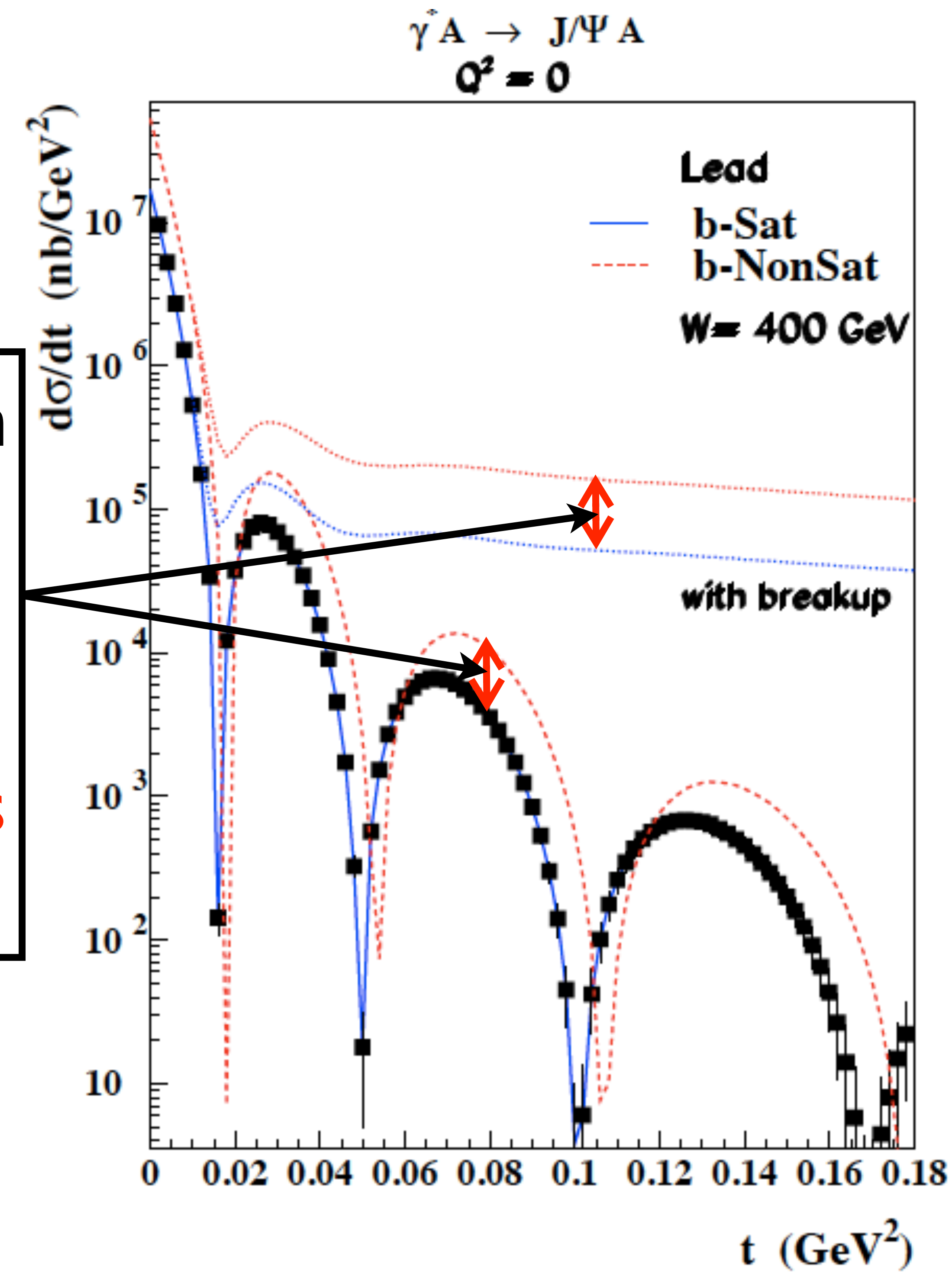


- Large extent in t with good precision.
- Sizable saturation effects expected.

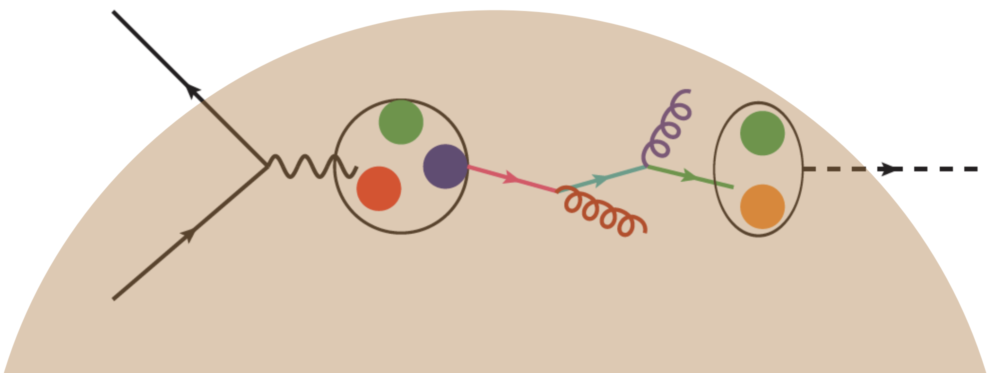


Radiation & hadronization:

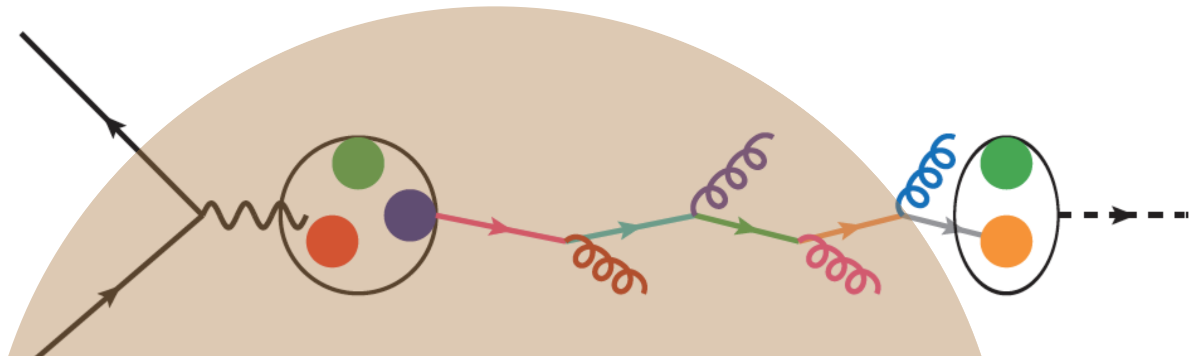
- Dynamics of QCD radiation and hadronization.
- Most relevant for particle production off nuclei and for QGP analysis in HIC.

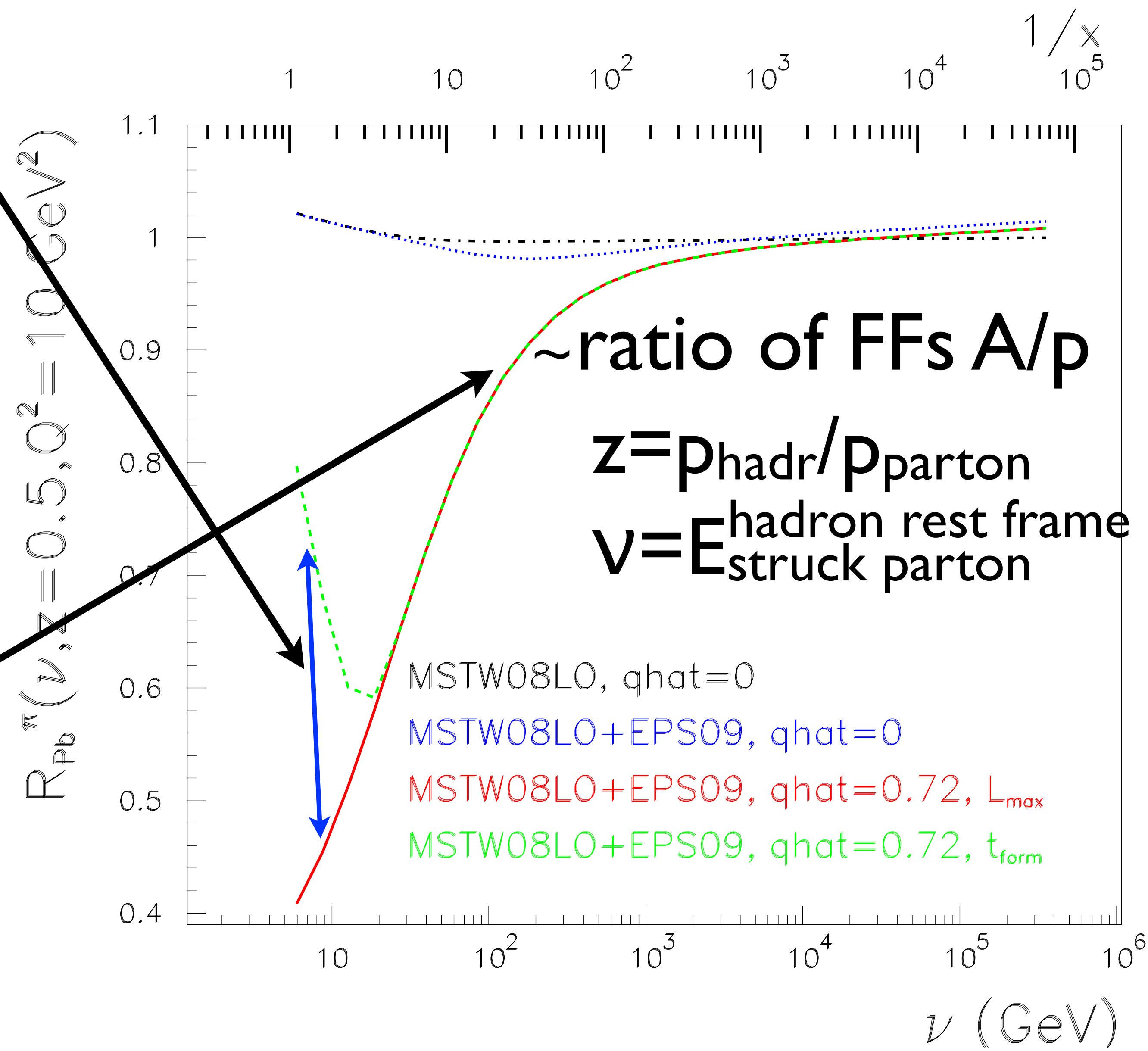
$$R_A^h(z,\nu) = \frac{1}{N_A^e}\frac{dN_A^h(z,\nu)}{d\nu\, dz} \Bigg/ \frac{1}{N_D^e}\frac{dN_D^h(z,\nu)}{d\nu\, dz}$$

- Low energy: hadronization inside → formation time, (pre-)hadronic absorption,...



- High energy: partonic evolution altered in the nuclear medium.





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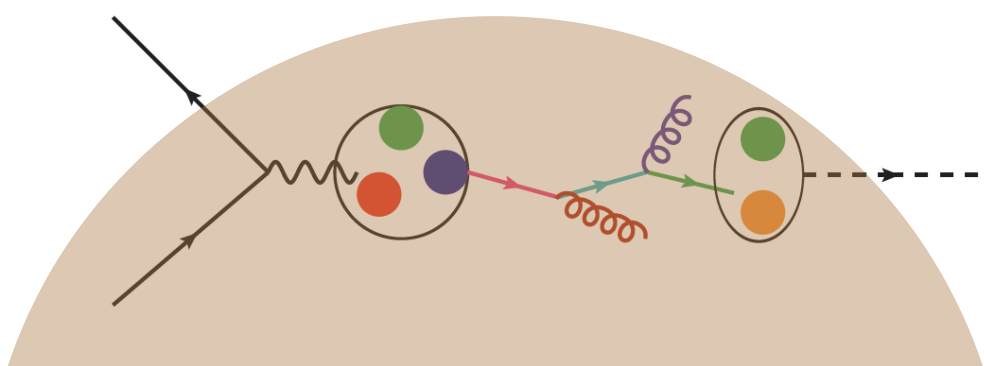

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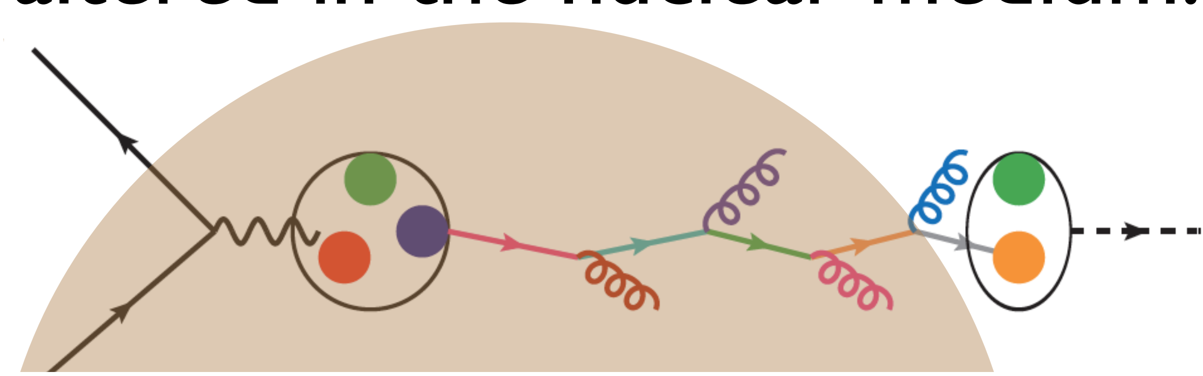
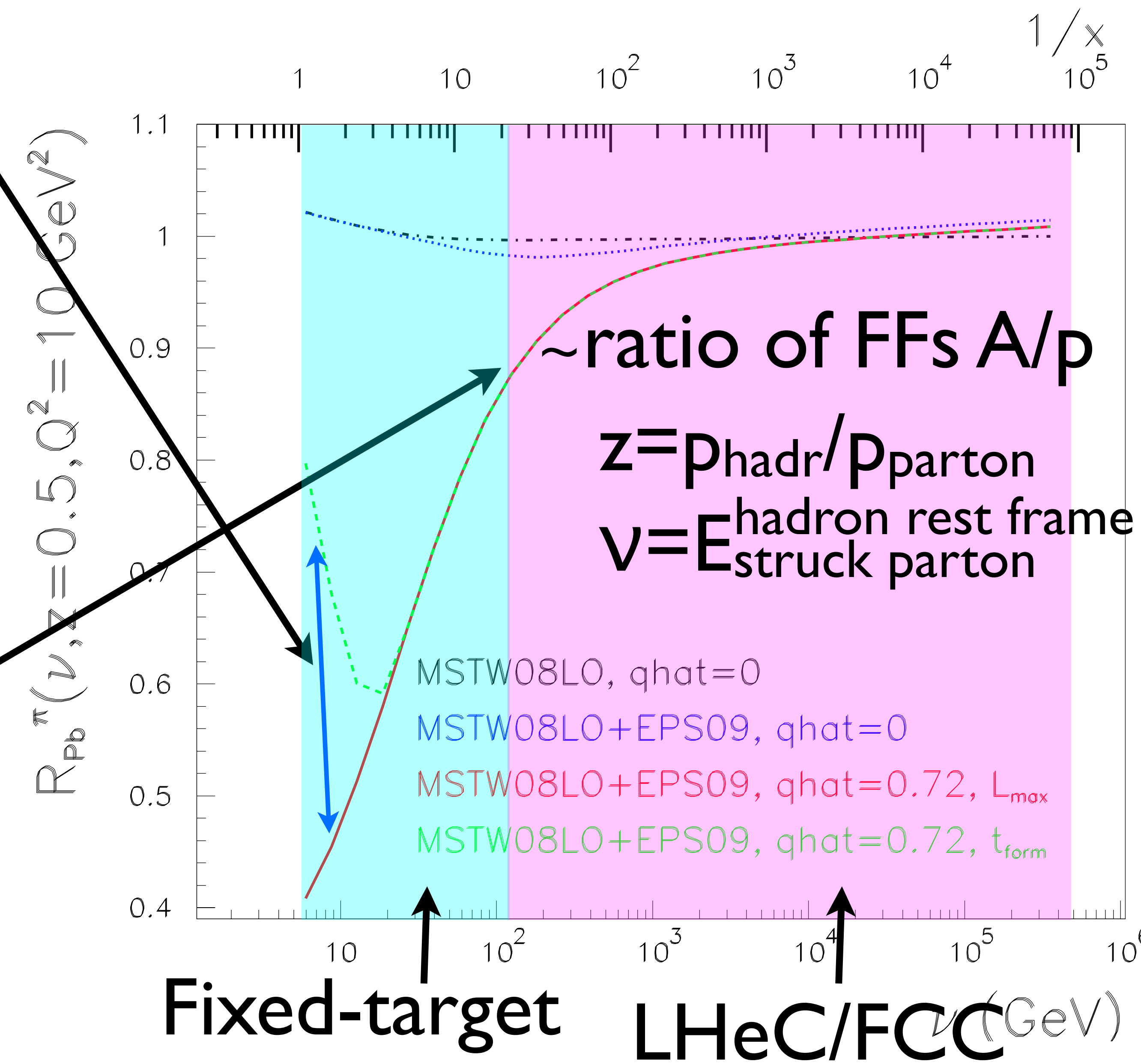
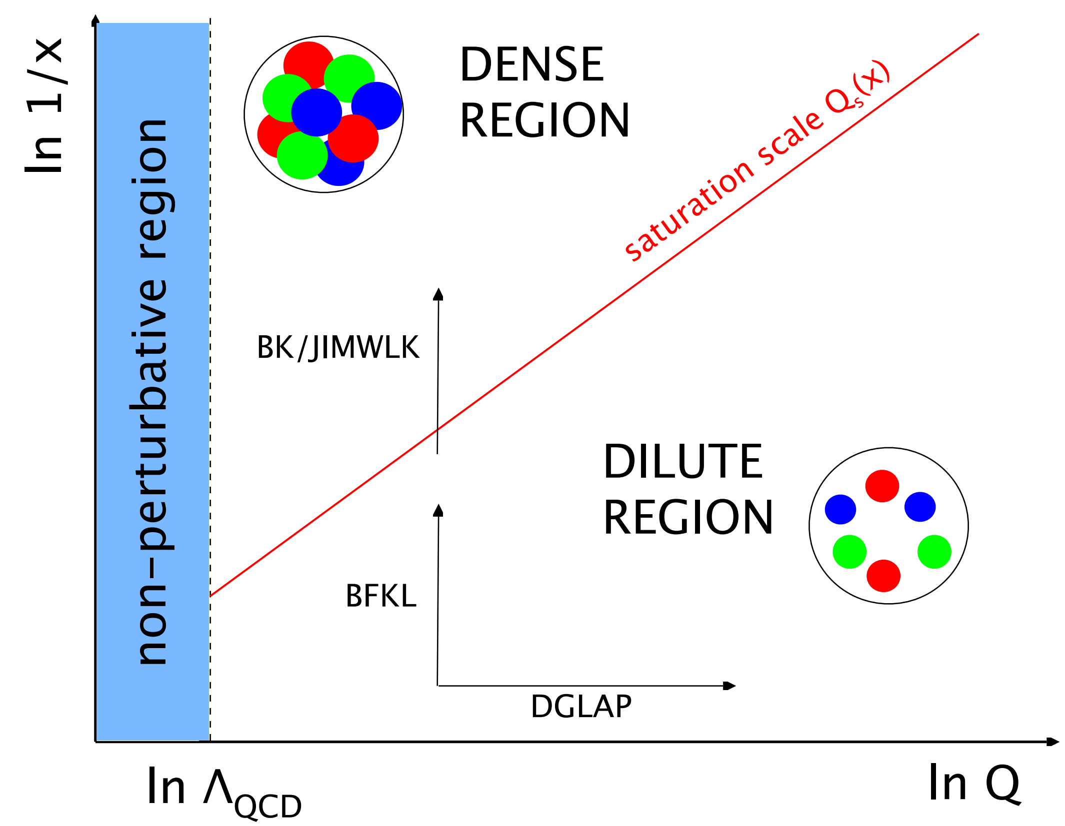
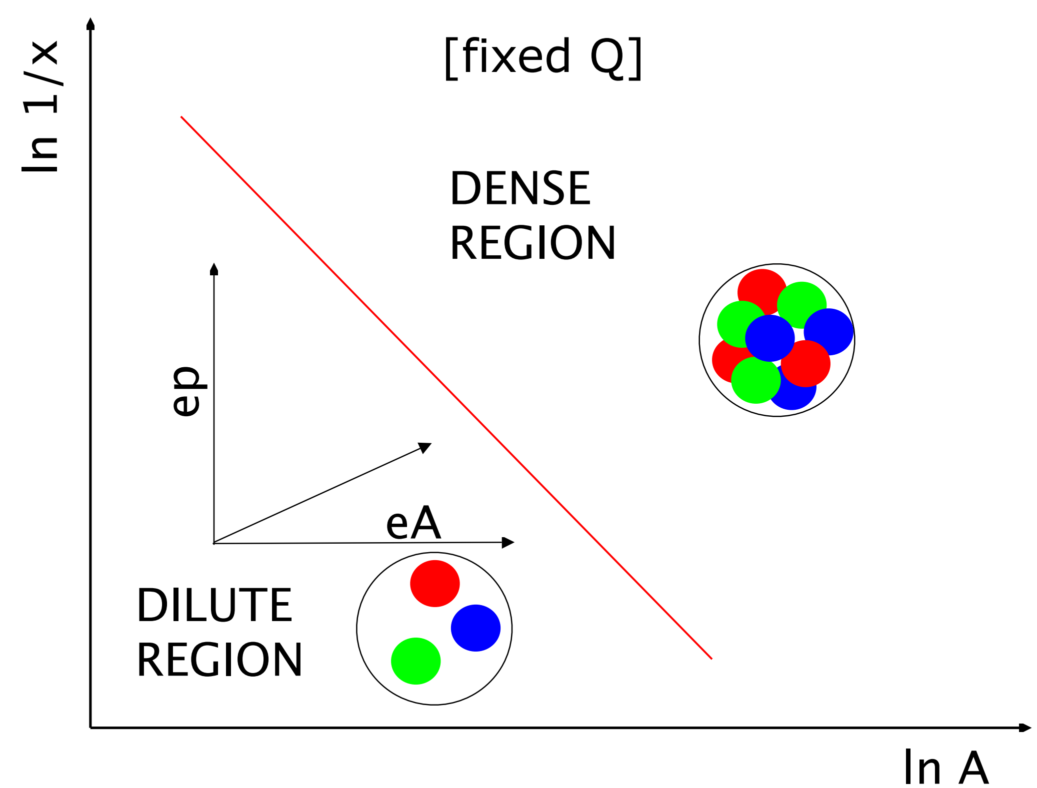




Summary:

- ***At the FCC-he***:
  - ➜ High-precision tests of collinear factorization(s) and determination of PDFs.
  - ➜ Unprecedented access to small x in p and A.
  - ➜ Novel sensitivity to physics beyond standard pQCD.
  - ➜ Stringent tests of QCD radiation and hadronization.
  - ➜ Transverse scan of the hadron/nucleus at small x.
  - ➜ ... with implications on our understanding of QGP.
- **ep AND eA are both essential to unravel the existence of new regimes of QCD at high energies.**





Summary:

• Several items have to be done/ improved:

➜ Refine DGLAP fits.

➜ Nuclear GPDs: nuclear DVCS etc.

➜ Monte Carlo generators.

➜ Studies on diffraction: separation of coherent from incoherent, nDPDFs, dijets,...

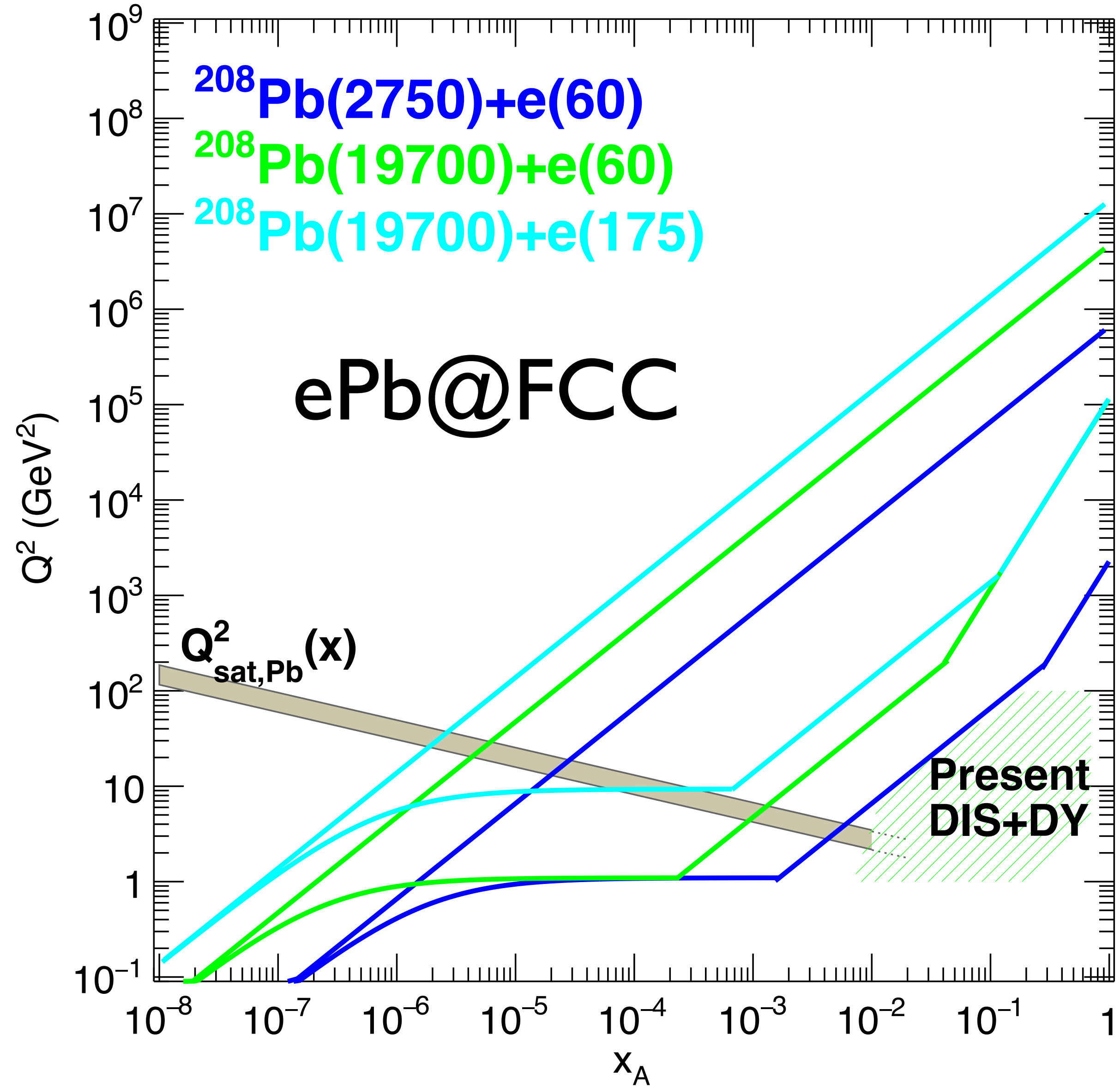
➜ Large x, EW bosons.

➜ eD.

➜ Jet reconstruction, angular decorrelation,...

➜ ...

→ Cooperation with EIC in some of these items possible.



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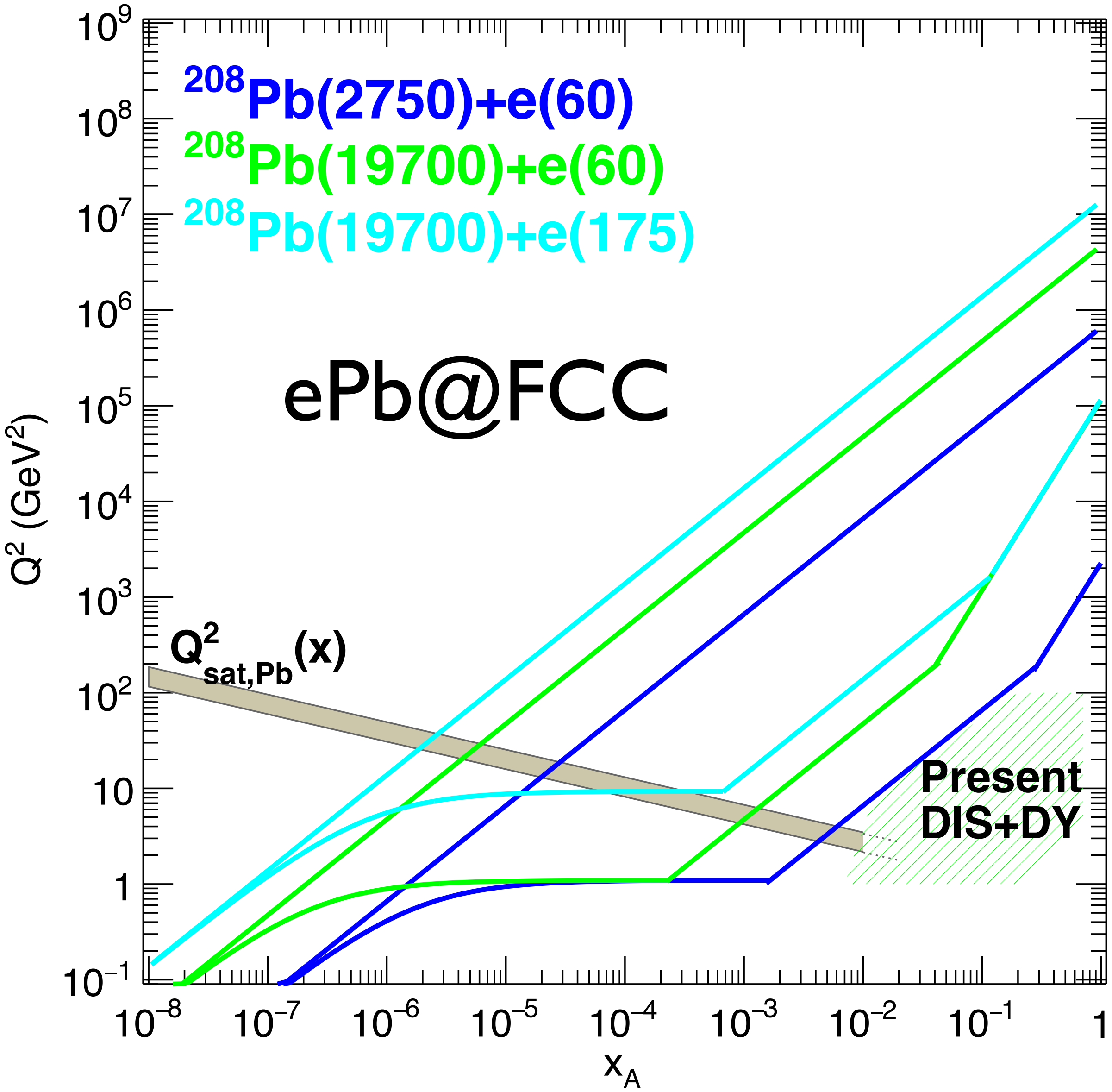


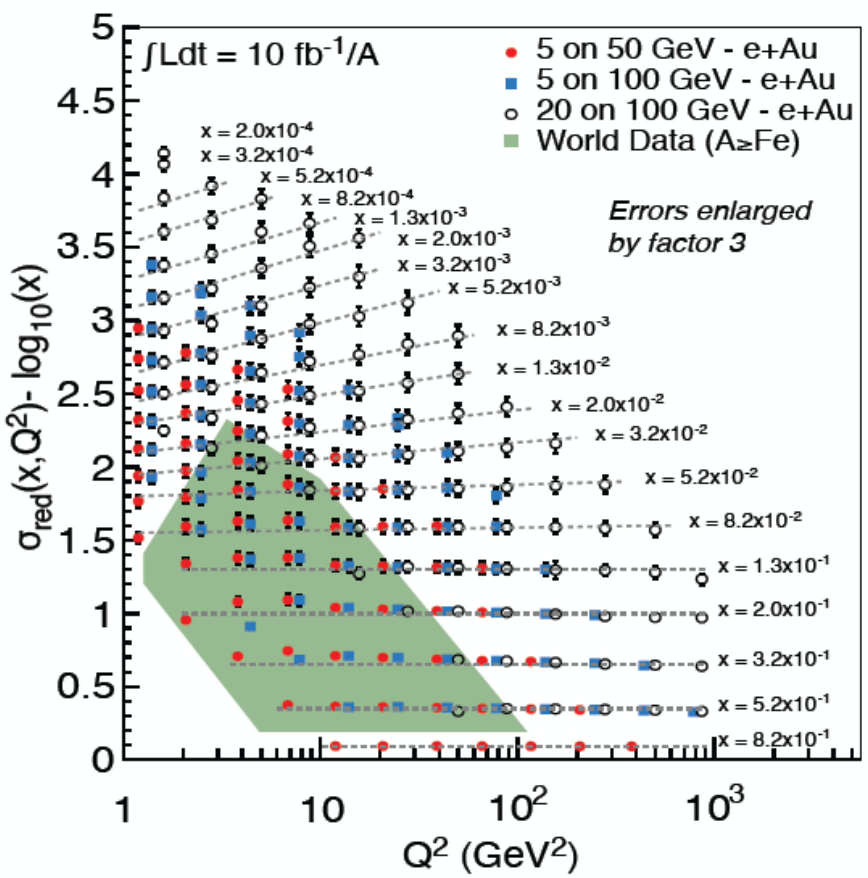
Special thanks to J. Jowett, M. and U. Klein, P. Newman and A. Stasto.

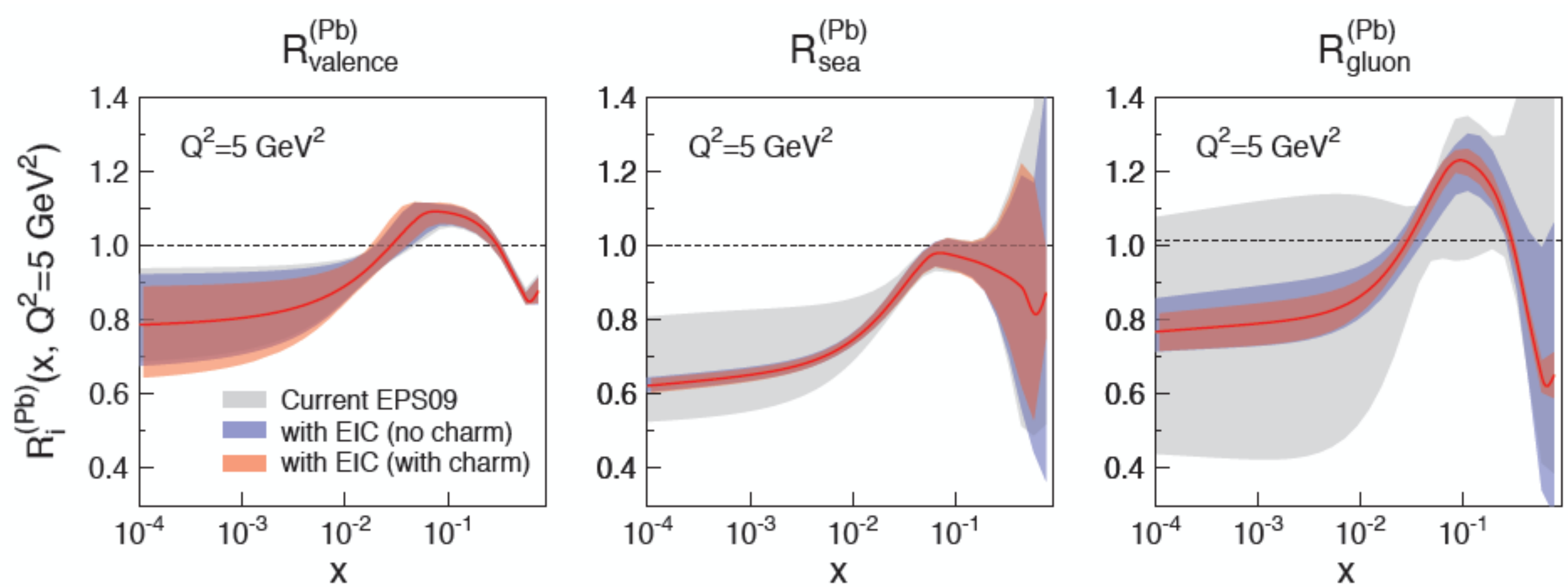
Many thanks for your attention!!!

Backup:

ICs and uncertainties:

- Sensitivity to the mathematical form of the initial conditions is a well-known issue in proton PDFs: NNPDF, PDF4LHC recommendation of comparing different sets, HERAPDF2.0 studies,…
- In our case: determination of nPDFs beyond data…





EIC example, Lamont at IS2014

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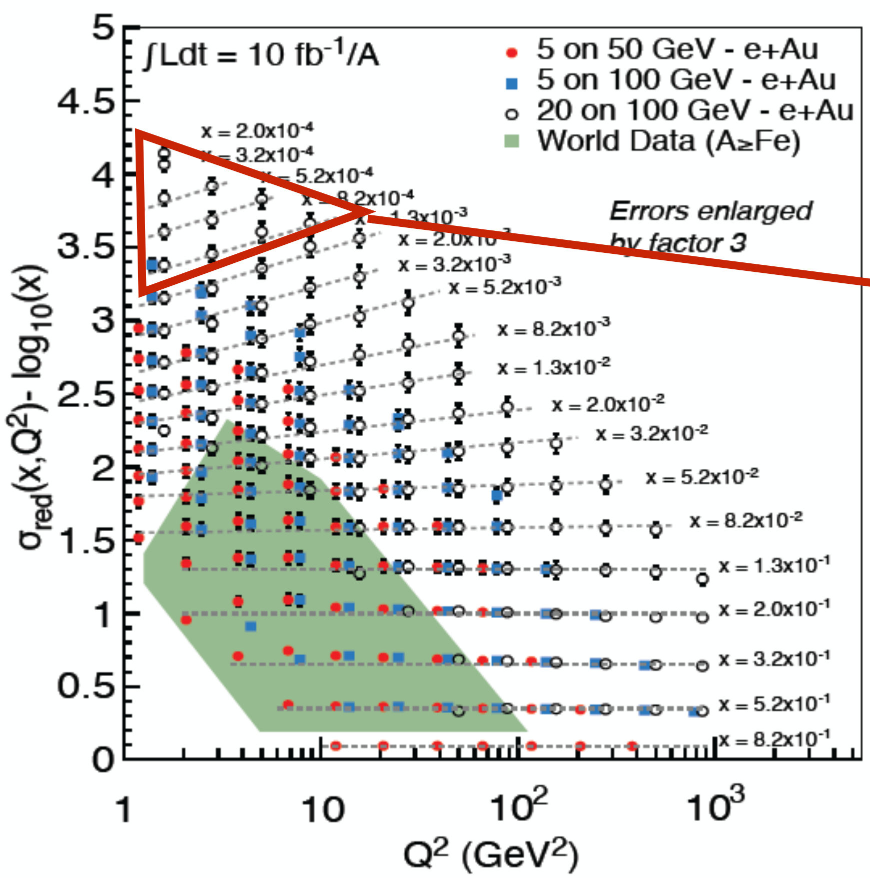
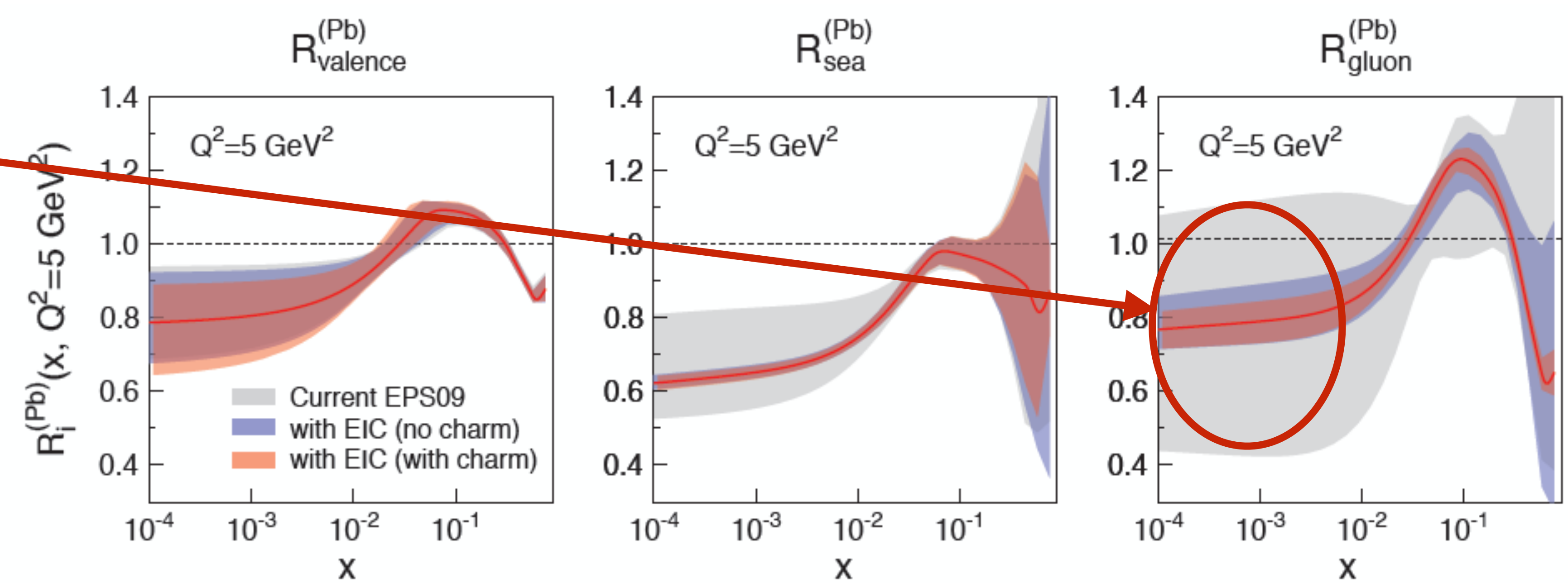


How?: mainly dictated by the shape of ICs



EIC example, Lamont at IS2014

$$\frac{\partial R^A_{F_2}(x,Q^2)}{\partial \log Q^2} \approx \frac{10\alpha_s}{27\pi}\frac{xg(2x,Q^2)}{\frac{1}{2}F_2^{\mathrm{D}}(x,Q^2)}\left\{R^A_g(2x,Q^2) - R^A_{F_2}(x,Q^2)\right\}$$

hep-ph/0201256

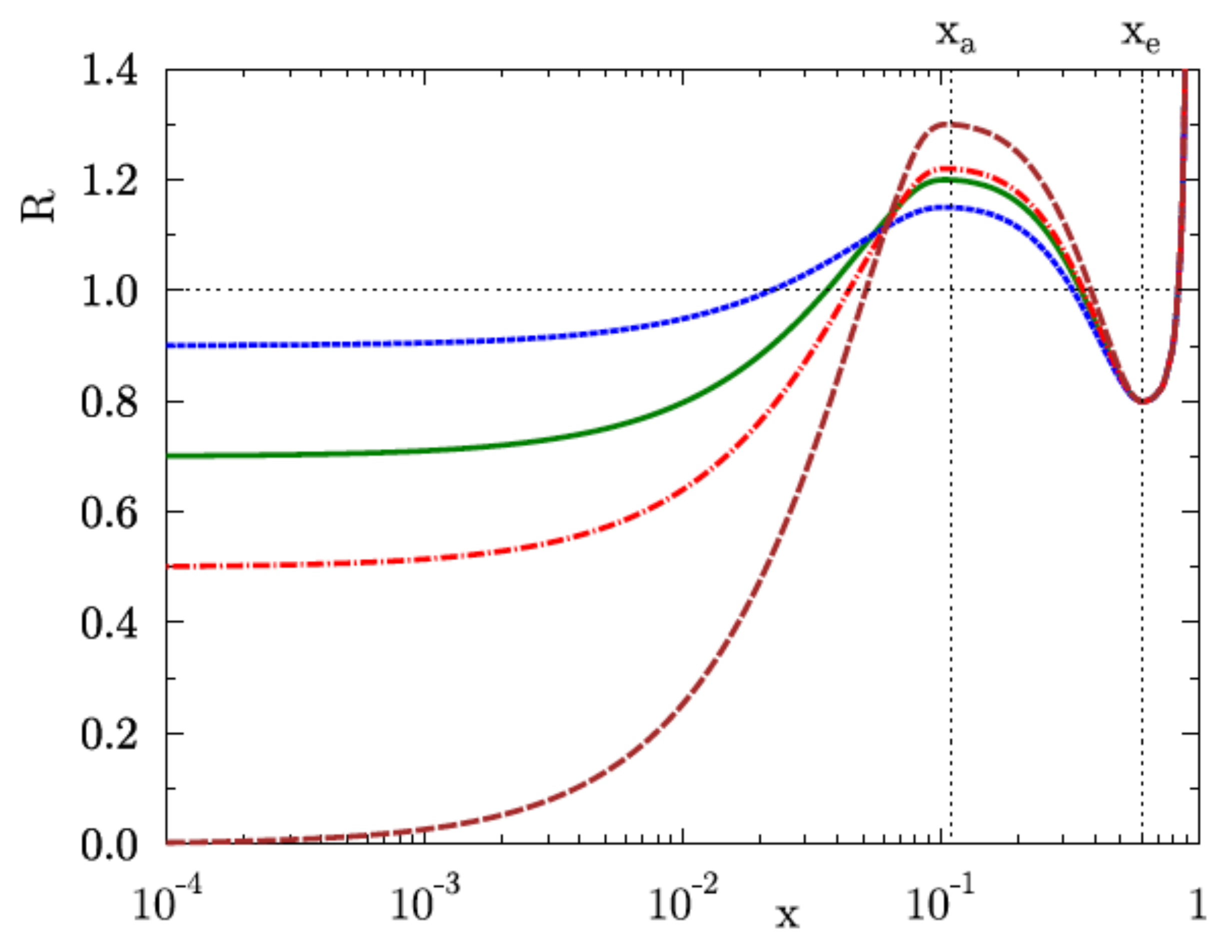
EPS09:

- Very little freedom at small x.

  The fit function in EPS09:

$$R^{\mathrm{EPS09}}(x) = \begin{cases} a_0 + (a_1 + a_2 x)\left(e^{-x} - e^{-x_a}\right) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

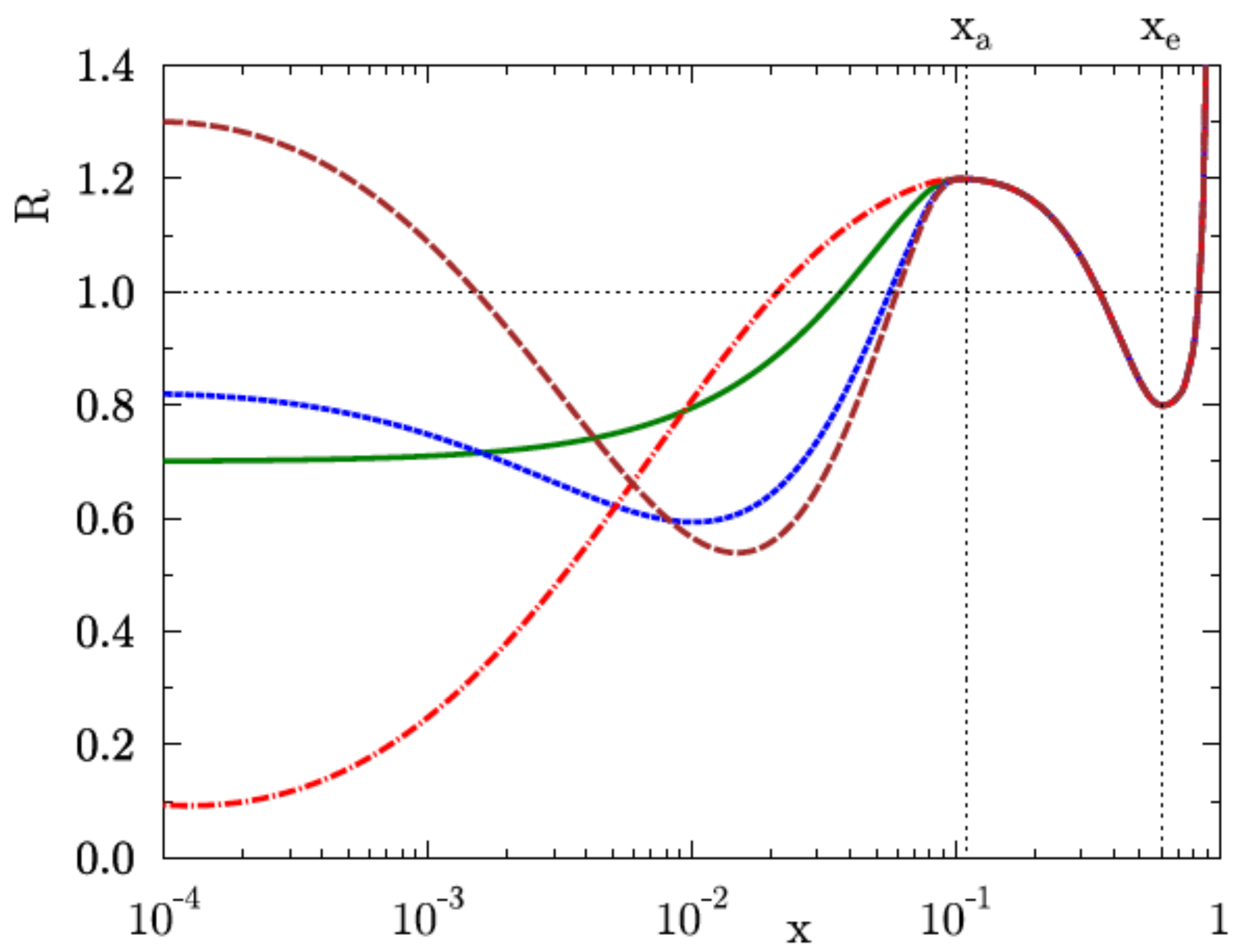
(power-law parametrization of A-dependence at x_a, x_e, and $x \to 0$)



New ICs:

- Use a far more flexible form to reduce the bias at small x:

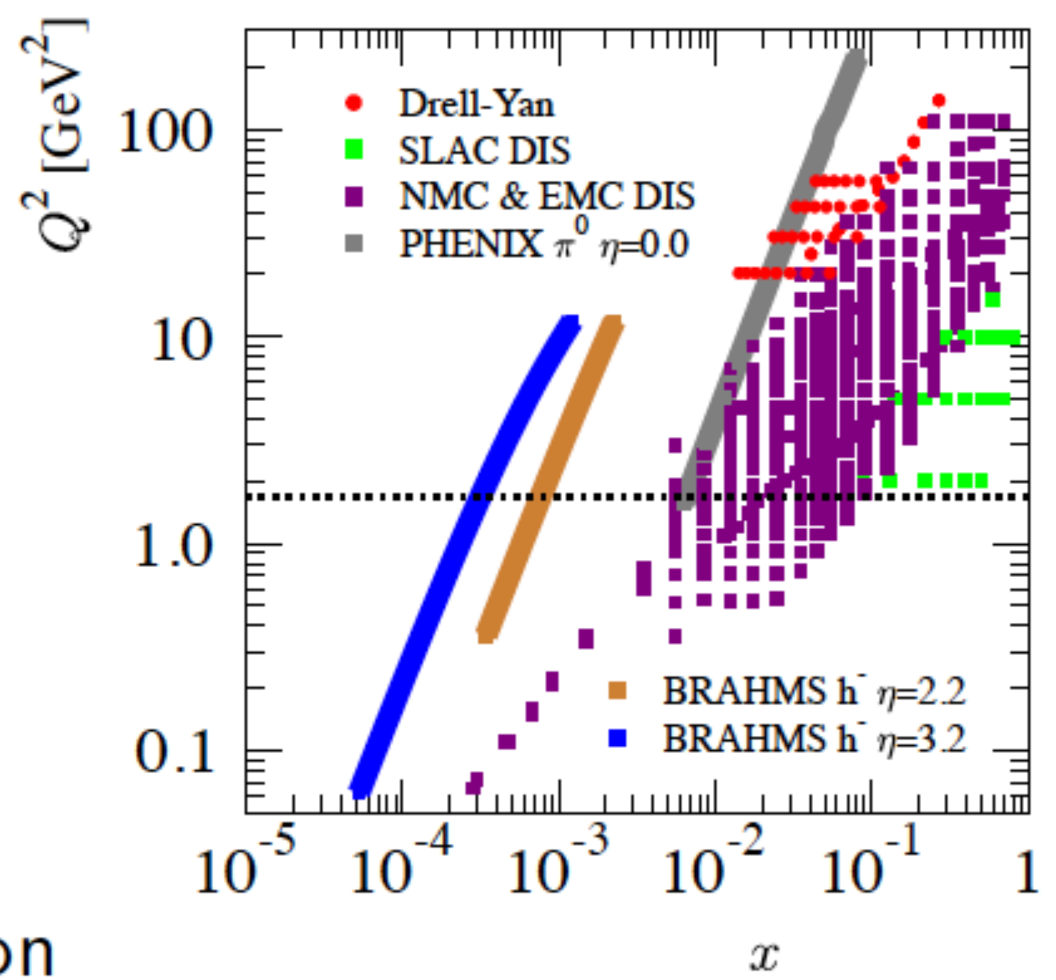
$$R(x \le x_a) = a_0 + a_1(x - x_a)^2 + \sqrt{x}(x_a - x)\left[a_2 \log\left(\frac{x}{x_a}\right) + a_3 \log^2\left(\frac{x}{x_a}\right) + a_4 \log^3\left(\frac{x}{x_a}\right)\right]$$



New fit framework:

- Include the same data (DIS, Drell-Yan, inclusive π^0) as in EPS09 (no LHC data yet) plus LHeC (neutral current) pseudo data.
- CTEQ6.6 as baseline (doesn't really matter which one)
- Flavour-independent nuclear modifications at $Q_0 = 1.3\,\mathrm{GeV}$

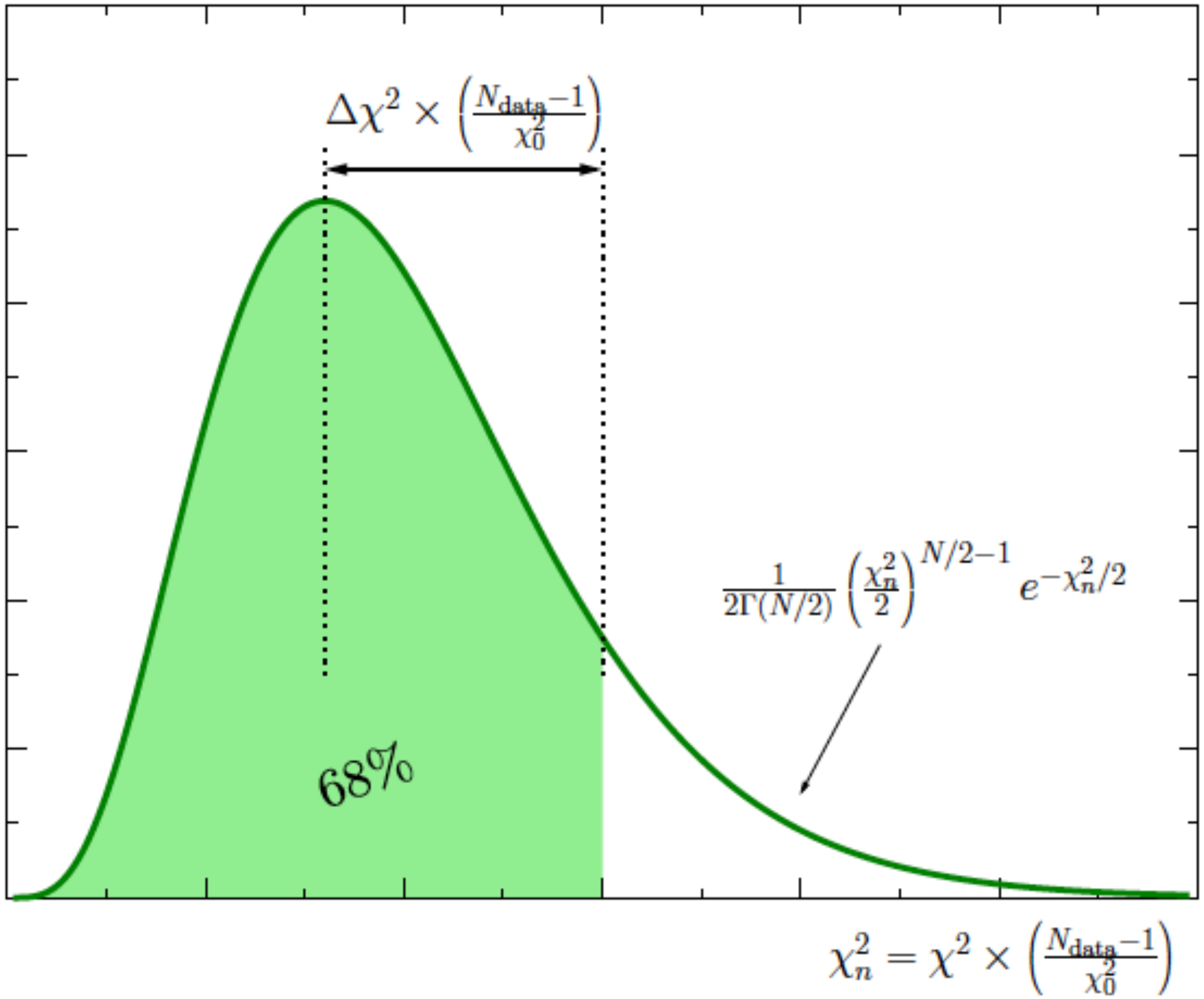
$R_V(x, Q_0)$ for both valence quarks
$R_S(x, Q_0)$ for light sea quarks
$R_G(x, Q_0)$ for gluons



- Charged-current data will be added later on to study the flavour dependence
- Cross-sections at NLO in the SACOT heavy-quark scheme (as CTEQ6.6)
- Robust Levenberg-Marquardt minimization method

New fit framework:

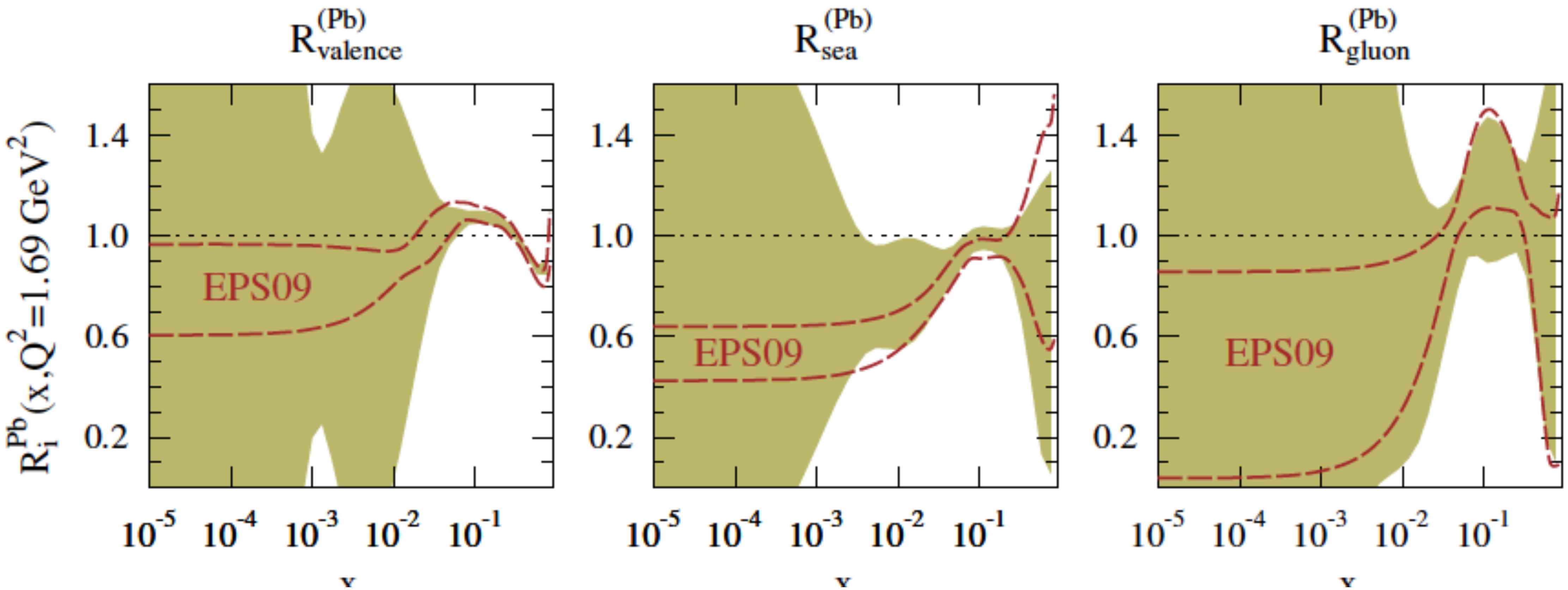
Standard Hessian uncertainty analysis (a la CTEQ, MSTW,...) with $\Delta\chi^2$ determined from the expected behaviour of probability distribution for the global χ^2



Gives $\Delta\chi^2 \approx 17$ (without or with the pseudodata)

New fit framework:

The baseline fit using the new fit functions: no control over small x!



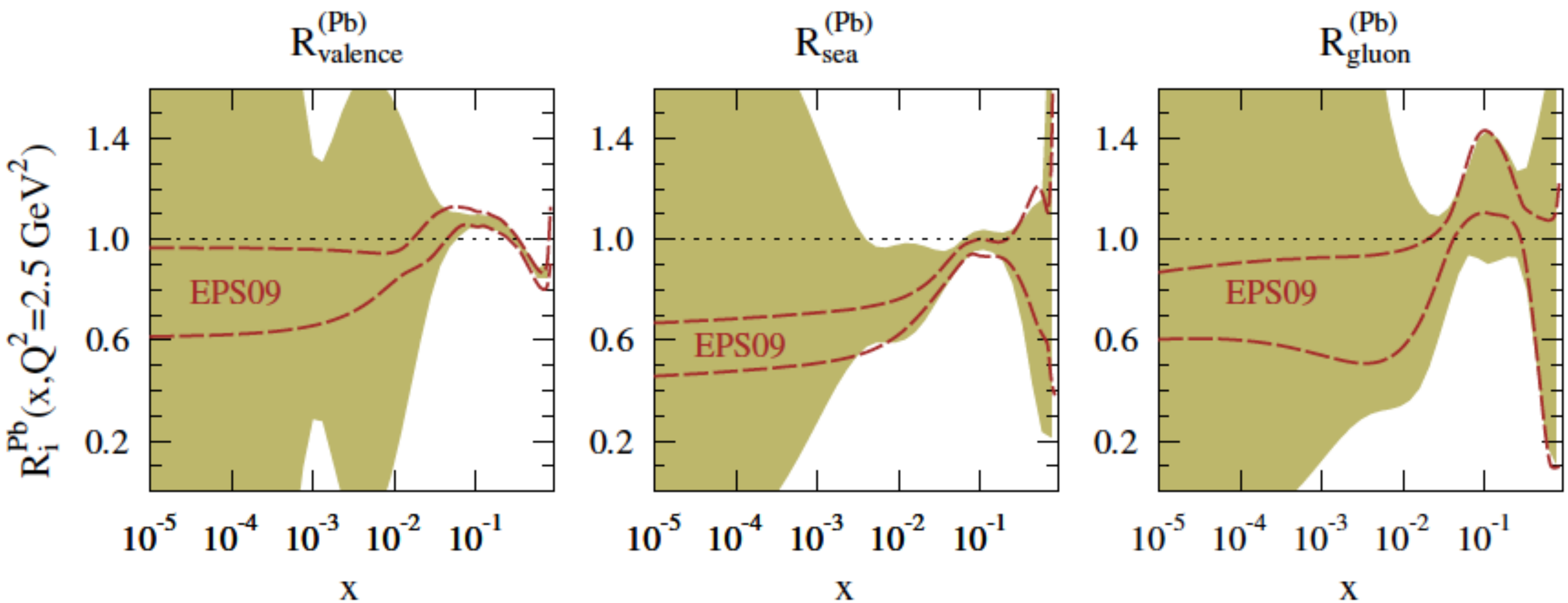
The lower bound restricted here by $F_L(Q^2 = 2\,\mathrm{GeV}^2, x > 10^{-5}) > 0$

Maybe against "physical intuition" (small-x theory predicts shadowing, $R_i < 1$), but consistent with the data.

E.g. in EPS09, small-x shadowing was essentially built in

New fit framework:

The Q^2 dependence partly smooths out the differences in gluons



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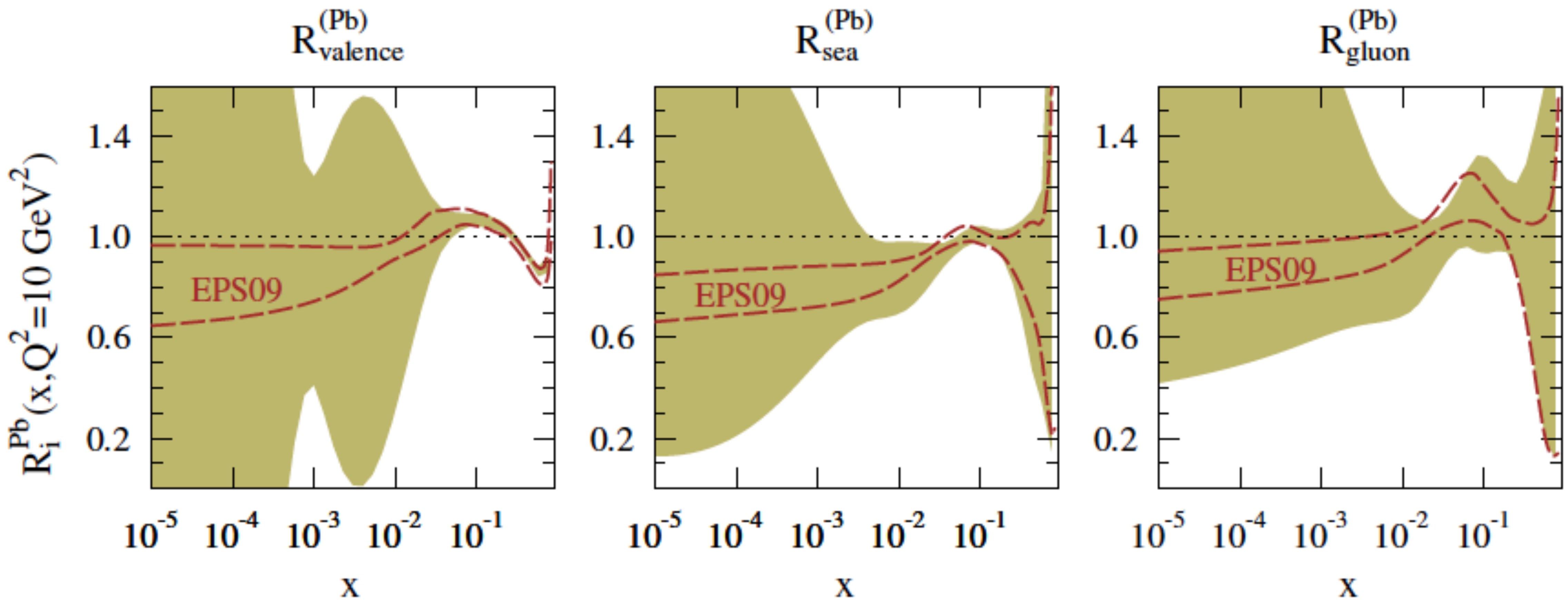


Pseudodata:

- Assume $\mathcal{L}_{\rm ep} = 10\,{\rm fb}$, $\mathcal{L}_{\rm ePb} = 1\,{\rm fb}$ (per nucleon)
- Top LHC energies: 7/2.75 TeV/nucleon.
- The pseudodata are obtained from ratios of reduced cross sections σ^i and relative uncertainties $\delta^i_{\rm uncor.}$ and $\delta_{\rm norm.}$ by

$$R_i = R_i(EPS09) \times \left[1 + \delta^i_{\rm uncor.} r^i + \delta_{\rm norm.} r^{\rm norm.}\right]$$

where

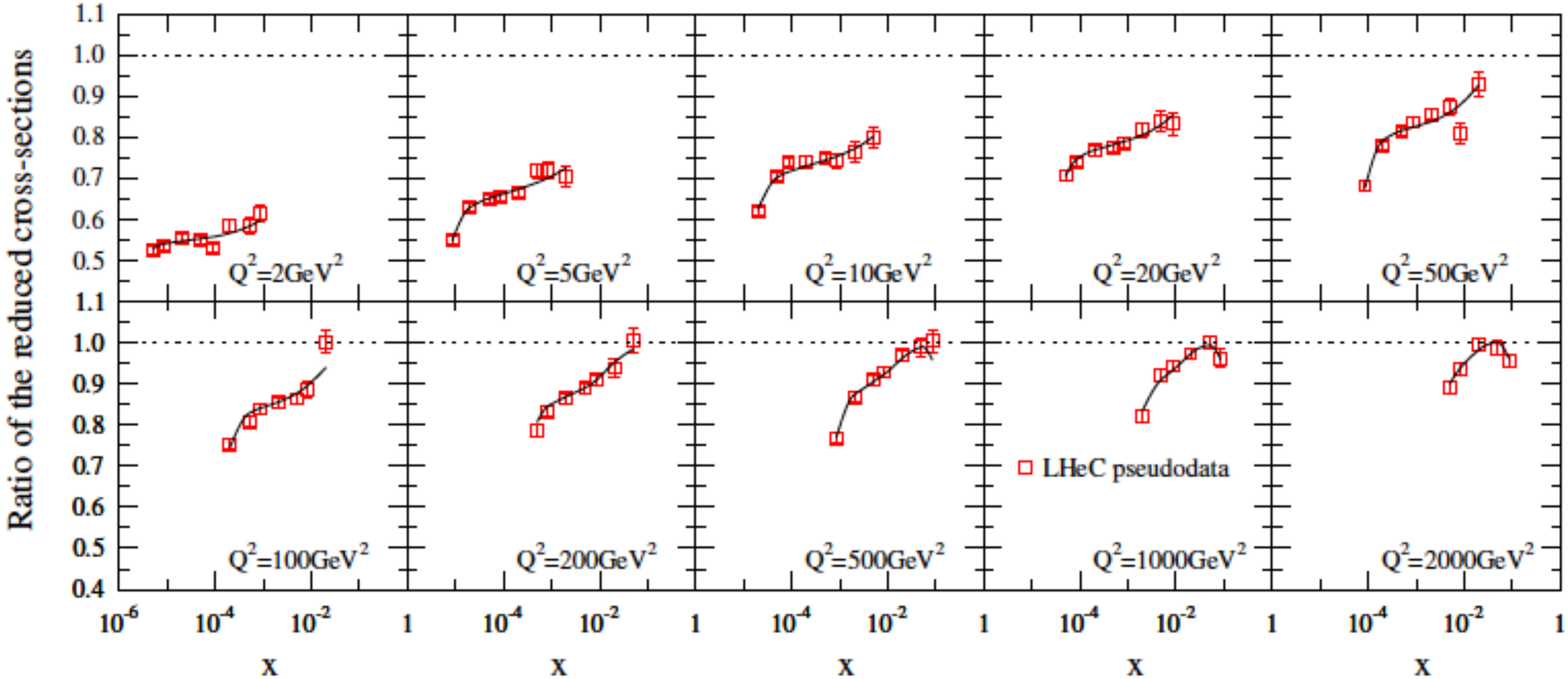
$$R_i(EPS09) = \frac{\sigma^i_{\rm ePb}(CTEQ6.6 + EPS09)}{\sigma^i_{\rm ep}(CTEQ6.6)},$$

and r^i and $r^{\rm norm.}$ are Gaussian random numbers.

- Typically $\delta^i_{\rm uncor.} < 2\%$ and $\delta_{\rm norm.} = 1.4\%$ (assuming that the uncertainties in e-p and e-Pb are uncorrelated)

Pseudodata:

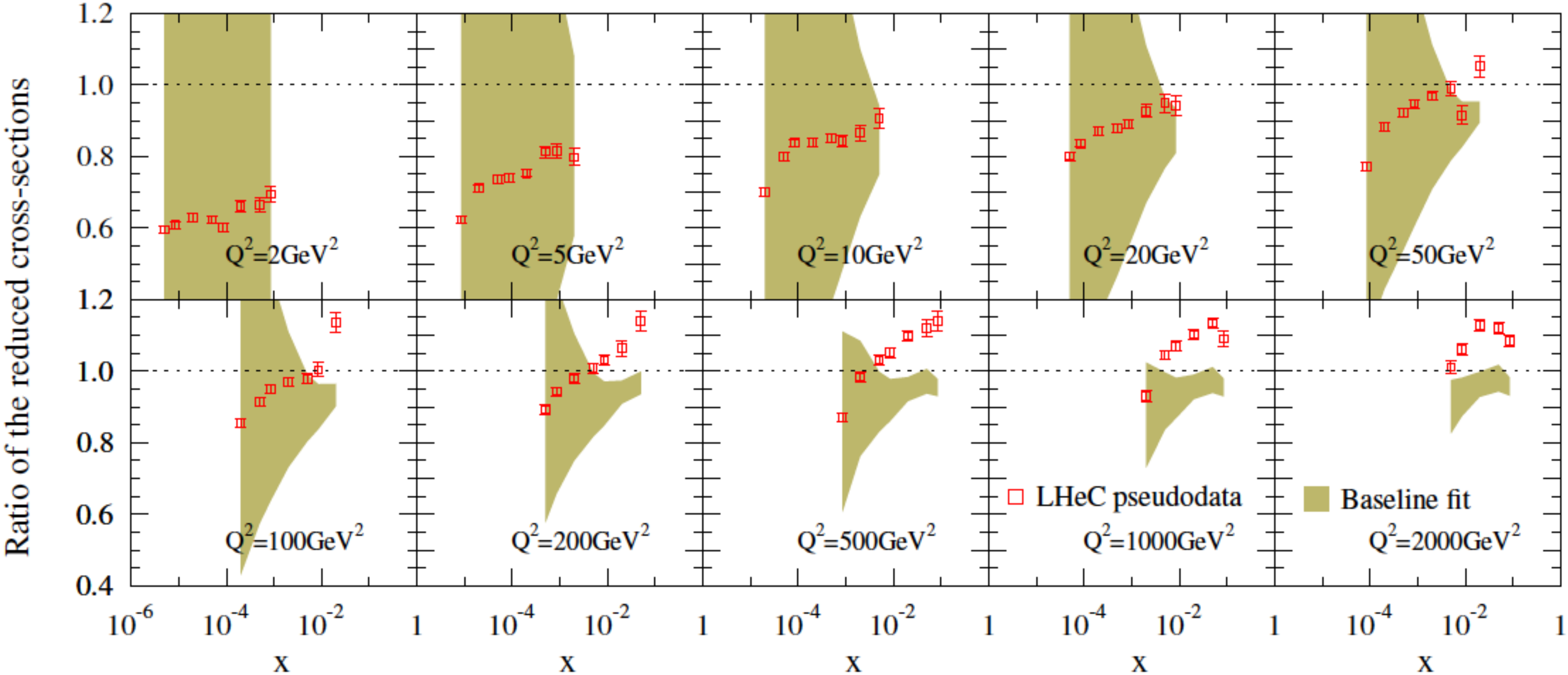
- Complete, new simulation: NC(+CC+c,b not yet used) with systematic uncertainties from a complete simulation.



Checked that $\chi^2/N_{\rm data}$ to the underlying truth (=EPS09 ;)) fluctuates about unity depending on the random numbers that got chosen

Pseudodata:

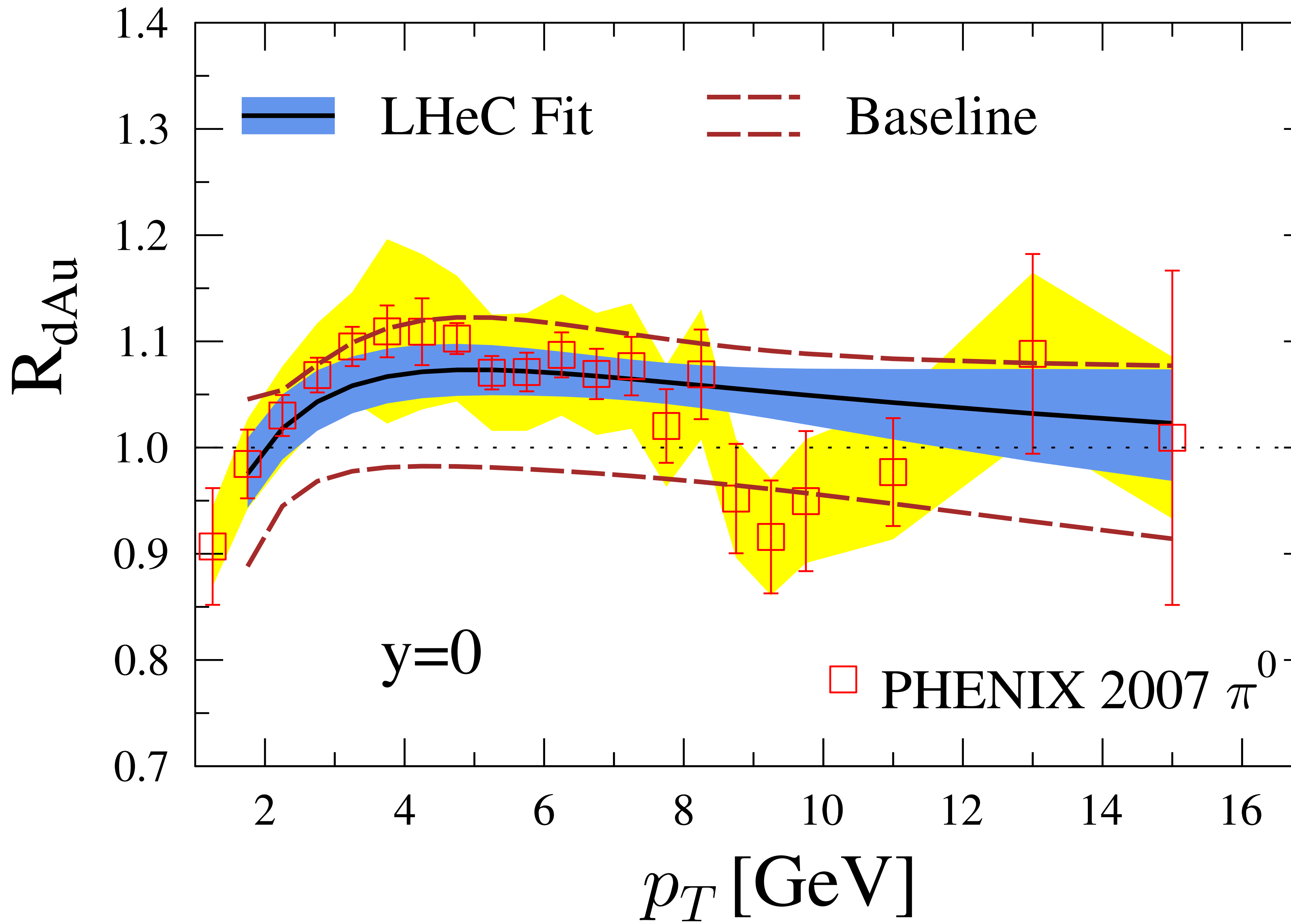
The error bands hugely exceed the data uncertainties



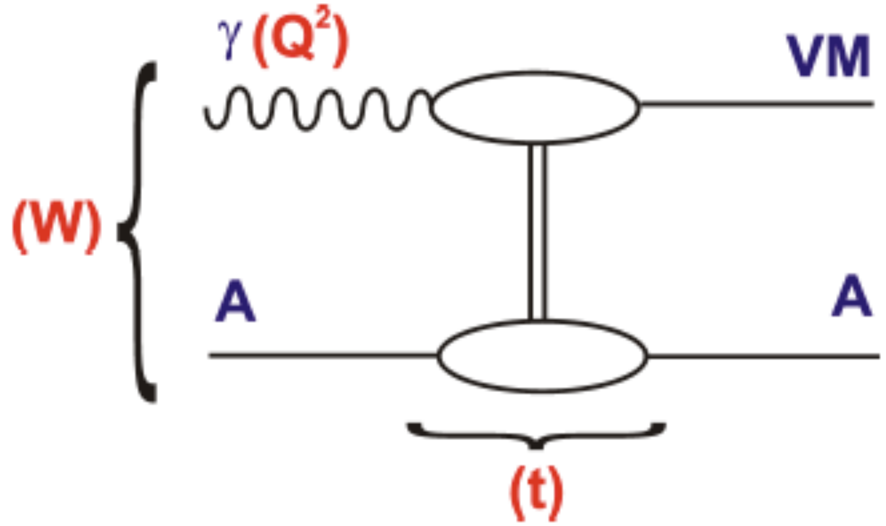
The "optimum" data normalization factor $f \sim 1.1$, hence the mismatch at large x

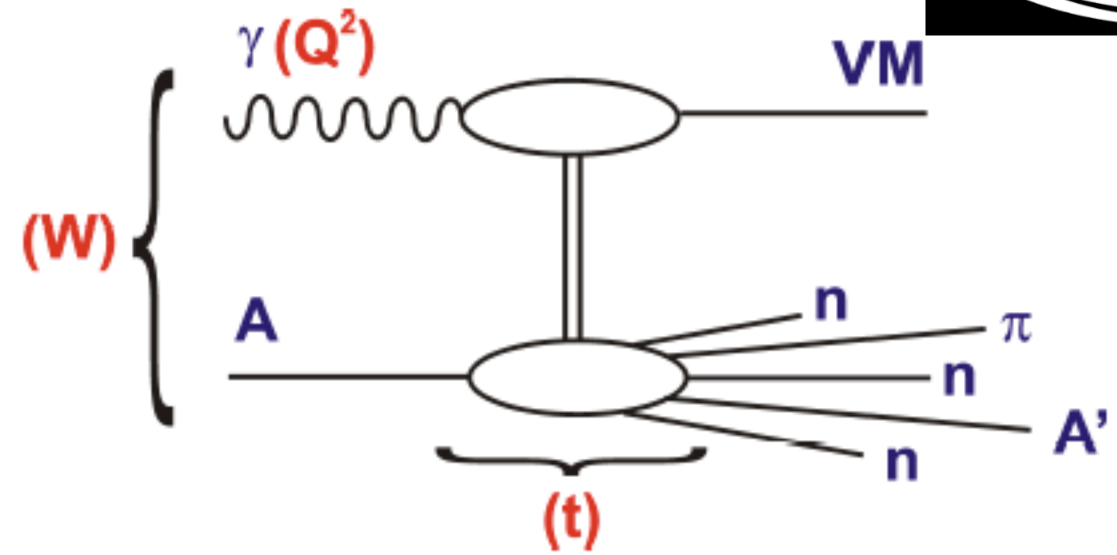
Compatibility: RHIC data

- Looking back to RHIC π^0 data - only direct constrain on glue at present (hopefully to be substituted by LHC (di)jets):



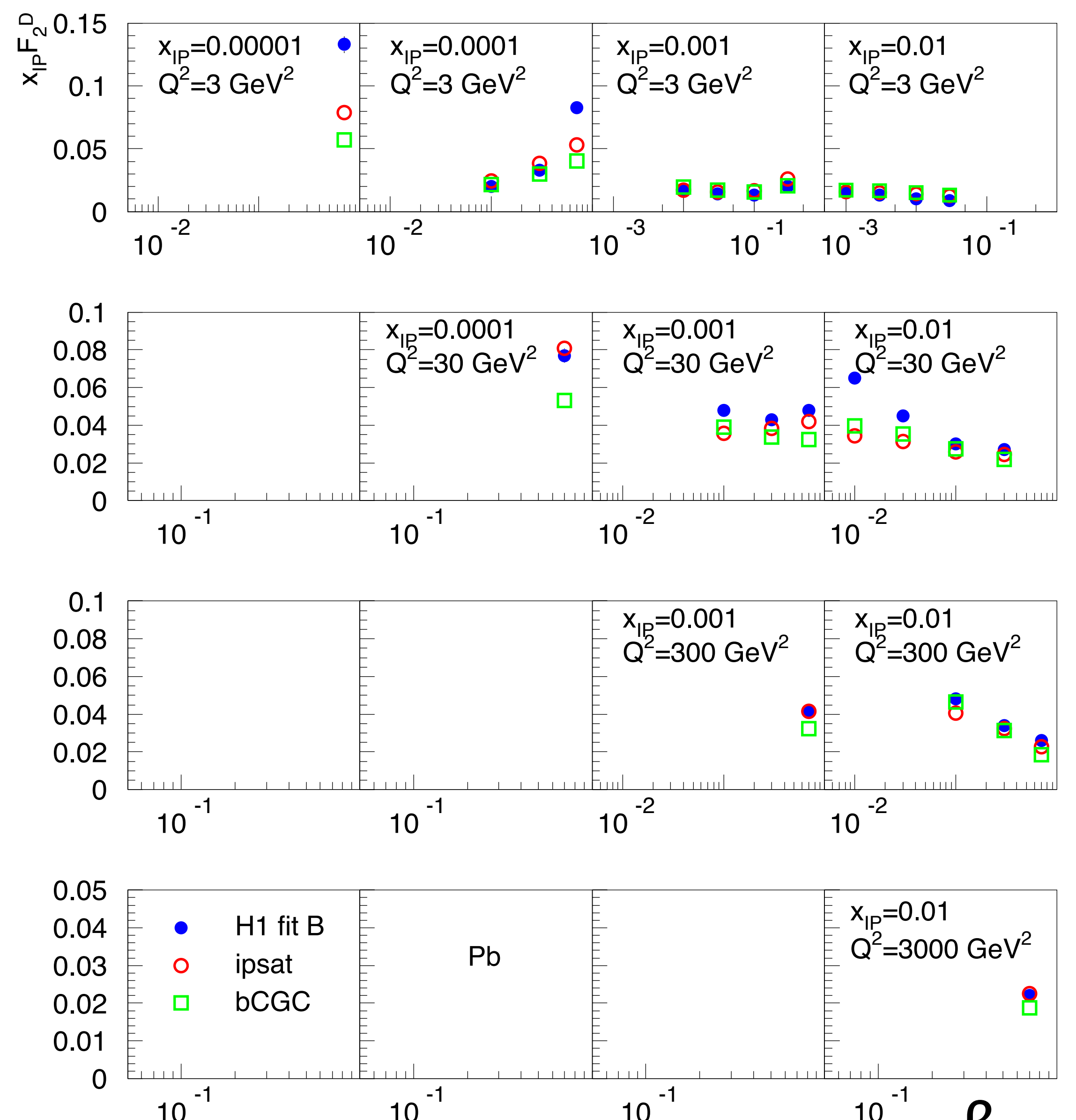
Diffractive DIS:



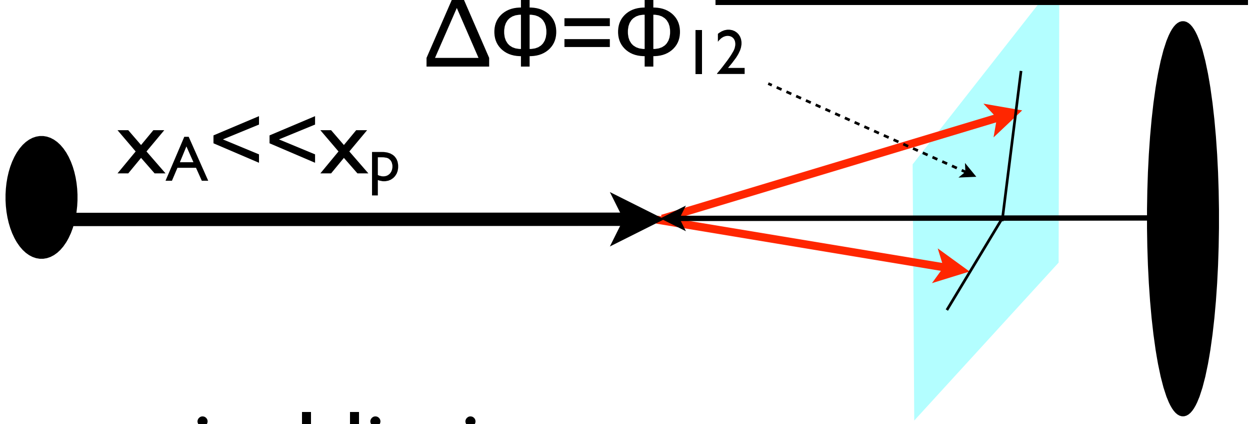


- Challenging experimental problem, requires Monte Carlo simulation with detailed understanding of the nuclear break-up.

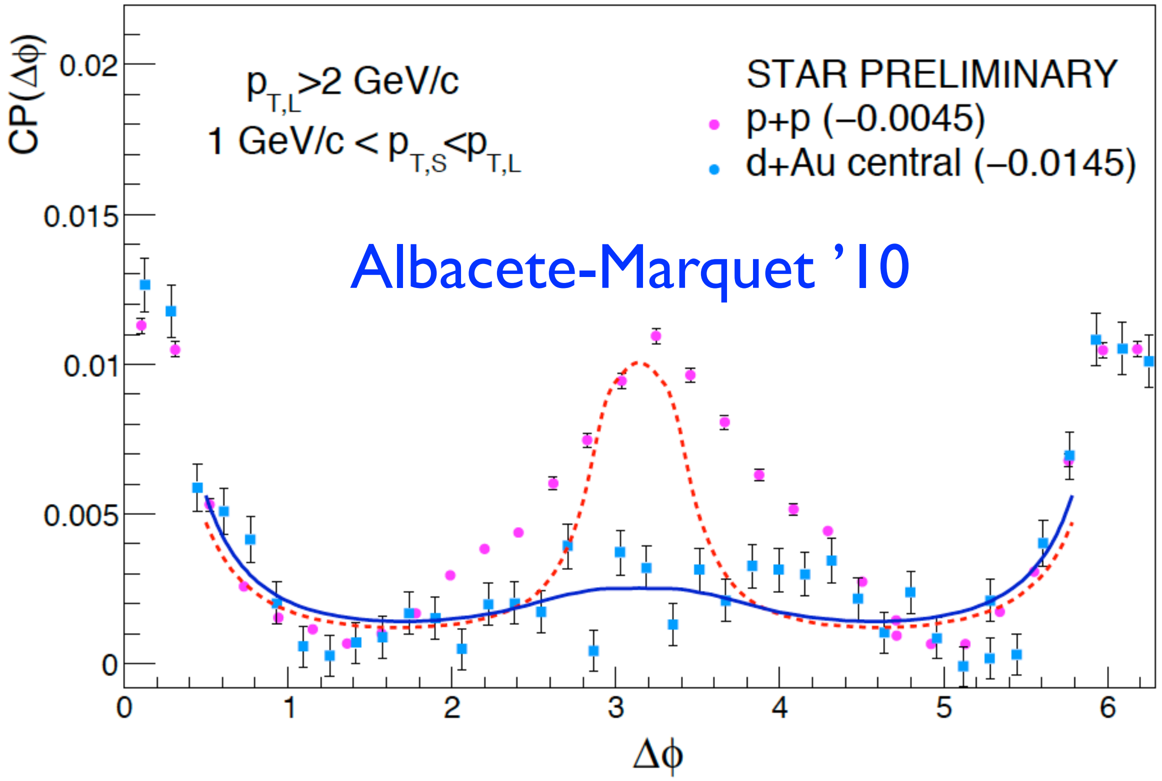
- For the coherent case, predictions available.



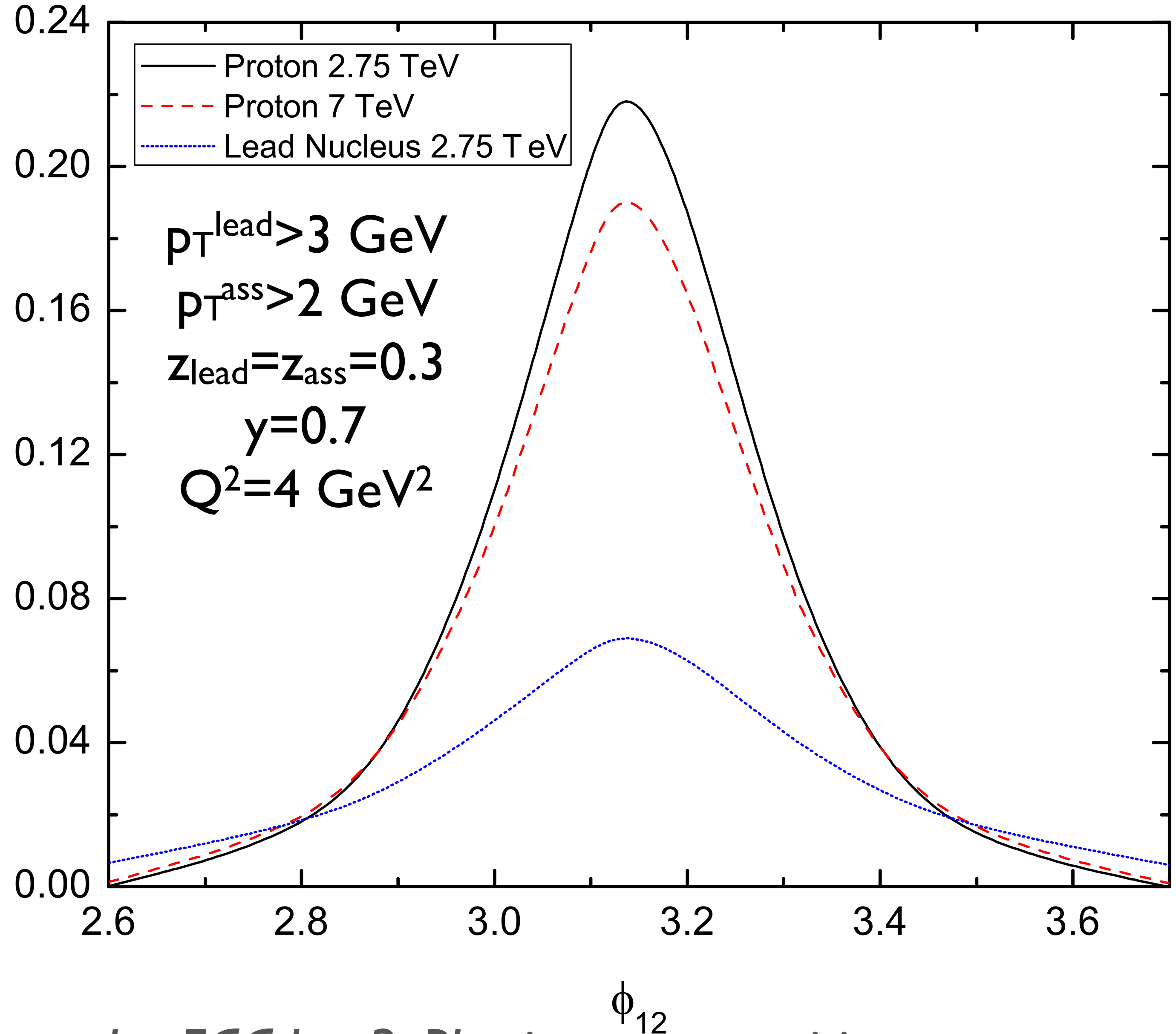
Azimuthal decorrelation:



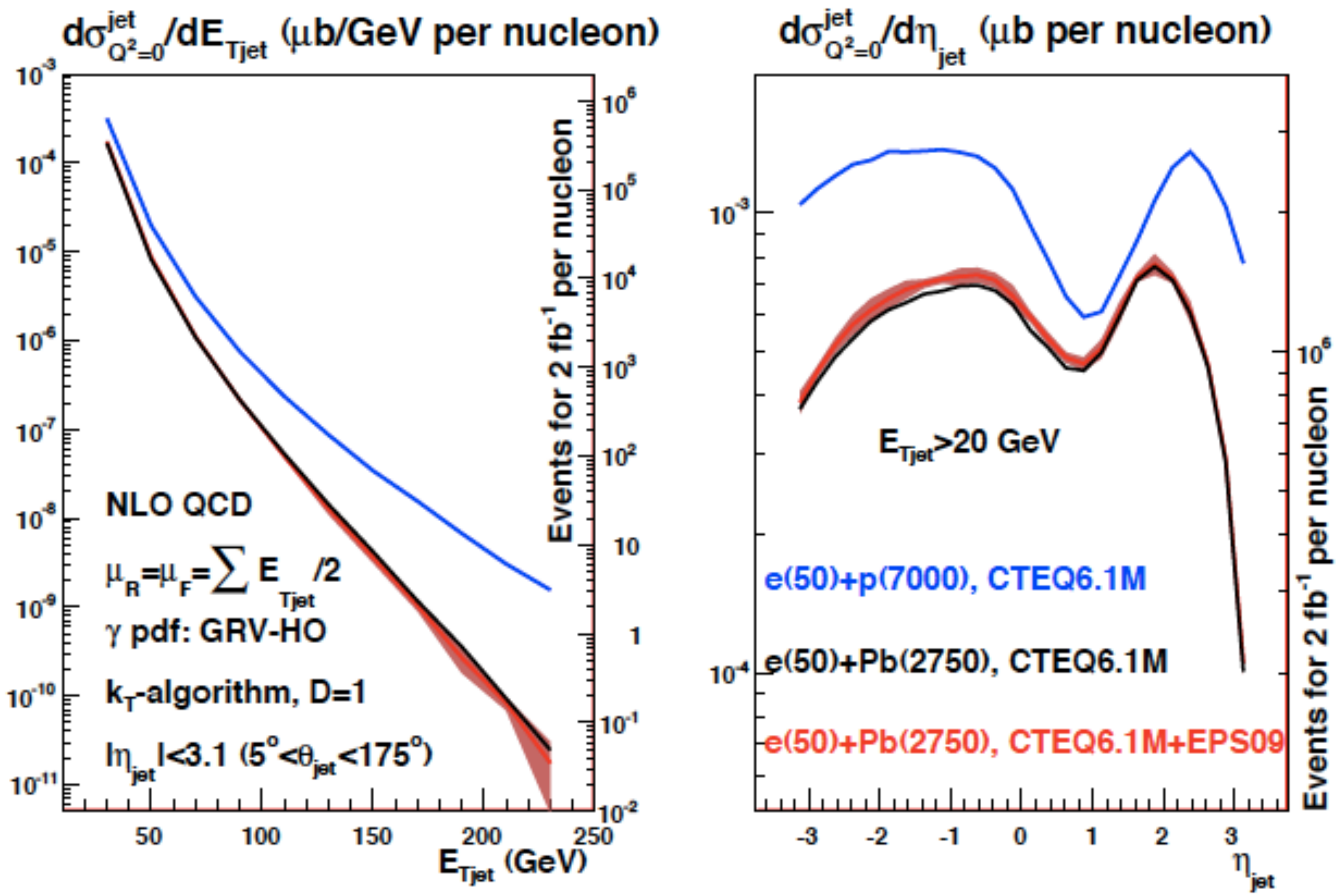
- Dihadron azimuthal decorrelation: currently discussed at RHIC as suggestive of saturation.
- It could be studied far from the kinematical limits.



$$C(\phi_{12}) = \frac{1}{\frac{d\sigma(\gamma^* N \to h_1 X)}{dz_{h1}}} \frac{d\sigma^{\gamma^* N \to h_1 h_2 + X}}{dz_{h1} dz_{h2} d\phi_{12}}$$



Jets:



- Jets: large E_T even in eA.
- Useful for studies of parton dynamics in nuclei (hard probes), and for photon structure.
- Background subtraction, detailed reconstruction pending.